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QUANTIFYING THE BENEFITS TO THE NATIONAL ECONOMY FROM SECONDARY APPLICATIONS OF NASA TECHNOLOGY

Prepared by
MATHEMATICA, INC.
Princeton, N. J. 08540
for NASA Headquarters

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16. Abstract

Over the past one and a half decades, NASA and advanced ærospace technology have become virtually synonomous in the minds of people the world over. Yet as impressive as America's accomplishments in space have been, people intimate with NASA's past and continuing research and development efforts recognize that these programs have fostered valuable technological spillovers as well.

This study investigates the feasibility of systematically quantifying the economic benefits of secondary applications of NASA related R&D. Based upon the tools of economic theory and econometric analysis, it develops a set of empirical methods and makes selected applications to demonstrate their workability. Analyses of the technological developments related to integrated circuits, cryogenic insulation, gas turbines, and computer programs for structural analysis indicated substantial secondary benefits accruing from NASA"s R&D in these areas.

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A. Introduction

1. Background

In the 1958 law establishing the National Aeronautics and Space Administration, Congress charged the Administration with conducting its research activities "so as to contribute ... to the expansion of human knowledge of phenomena in the atmosphere and space." Recognizing that such knowledge, like much of the knowledge generated by research, could also have potential applicability in non-aerospace sectors of the economy, Congress further directed that NASA "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." 1/

NASA's success in accomplishing its aerospace objectives is unquestionable. The achievements of the satellite programs, manned space flights, and exploration of the moon are dramatic and well-known. Less clear, however, is the extent to which the knowledge developed in the NASA programs has been useful outside its aeronautics and space applications. While literally hundreds of instances of non-aerospace applications, ranging from the cardiac pacemaker to gas turbines, have been cataloged, hardly anything is known of the quantitative economic significance of NASA's contributions. 2/

2. Objectives

The purpose of this study is to develop preliminary estimates of the economic benefits to the U. S. economy from secondary applications of "NASA technology". If technology is defined as the body of knowledge concerning how society's resources can be combined to yield economic goods and services, then NASA technology represents NASA's contribution to this body of technical knowledge. Secondary applications refer to uses of NASA-generated knowledge for purposes other than those primary mission-oriented ones for which the original R & D was done. These applications occur whenever a non-NASA entity, with or without encouragement from NASA, uses this knowledge in some economic activity.

This chapter explains the study's approach to measuring these benefits. The development of such an approach can be usefully viewed as the development of answers to three successive questions:

1) What are the economic benefits of technological advance?
2) How can empirical estimates of these benefits be derived?
3) What part of these benefits can be attributed to NASA?

The next three sections of this chapter consider each of these questions in some detail. The final section presents a brief guide to succeeding chapters.

B. What are the Economic Benefits of Technological Advance?

1. A Definition of Economic Benefits

In broad terms, the economic process involves the conversion of society's stock of resources into goods and services and the sale or exchange of these goods and services in the marketplace. This activity generates economic benefits by allowing people to consume and produce desired combinations of goods and services. To evaluate benefits in this sense, this study adopts an approach to valuation frequently employed by economists. This approach relies on individuals' own valuations of the benefits of any transaction, as evidenced in their "willingness to pay" for the opportunity to engage in the transaction. More specifically, the benefits of any transaction, such as the sale of a good or service, are defined as the maximum amount a buyer would be willing to pay for the good or service above what he actually pays, plus the maximum amount a seller would be willing to give up and still sell the good or service. [3/]

The economic benefits to a buyer or seller of a good or service are illustrated in Figure I.1. Panel A depicts the individual's demand curve for a product. It indicates that at lower prices a consumer is willing to buy more of a product, or, alternatively, that he is willing to pay less for each incremental unit of product purchased. For example, the consumer

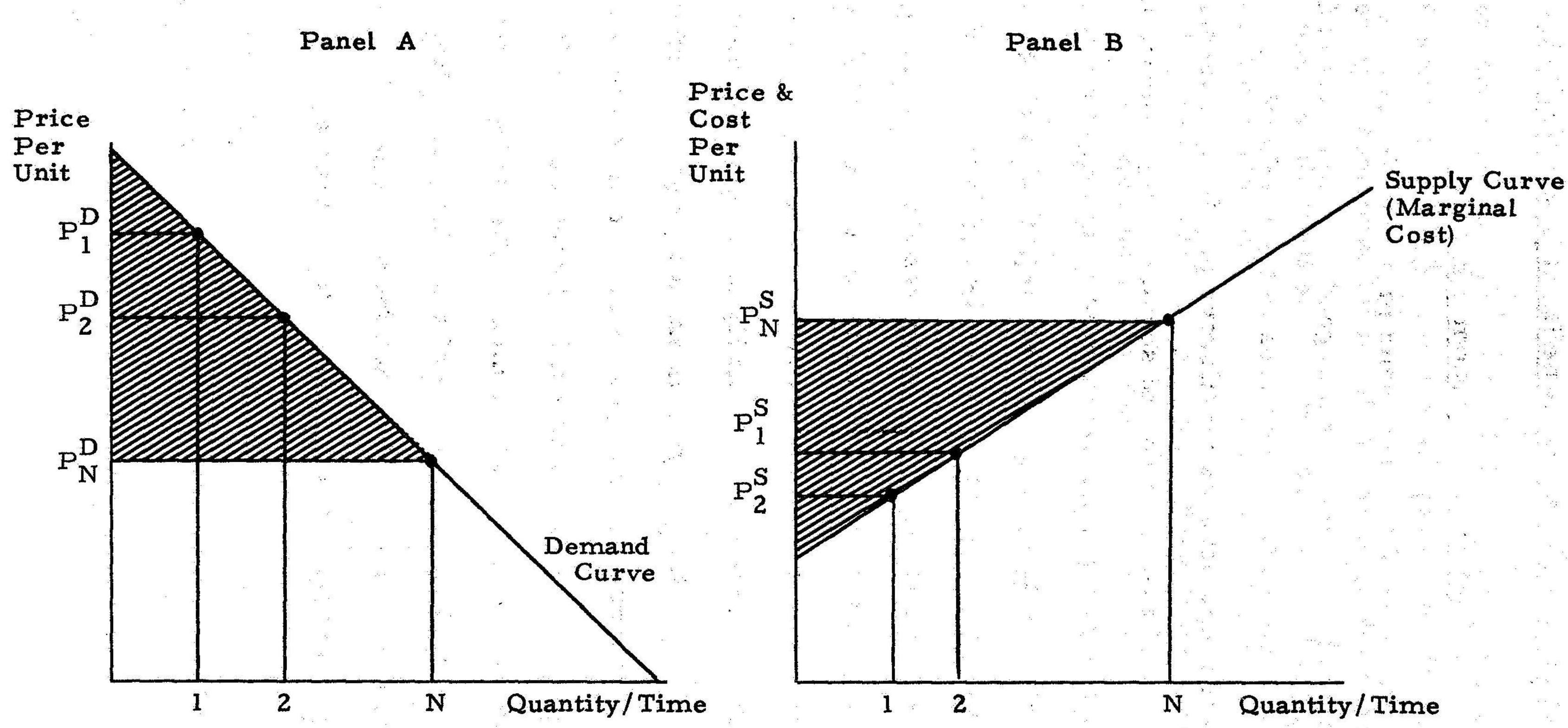

Panel A
Price
Per
Unit
P^D_1
P^D_2
P^D_N
Demand
Curve
1
2
N
Quantity/Time
Panel B
Price &
Cost
Per
Unit
Supply Curve
(Marginal
Cost)
P^S_N
P^S_1
P^S_2
1
2
N
Quantity/Time

Figure I.1

would have been willing to pay P_1^D for the first unit, P_2^D for the second unit, ..., P_N^D for the Nth unit. For N units the consumer would have been willing to pay the amount $\sum_i P_i^D$. If price P_N^D prevailed in the market, however, he would have been required to pay only $\left(P_N^D \cdot N\right)$. Thus, economic benefits in the amount $\sum P_i^D - \left(P_N^D \cdot N\right)$, which corresponds in the continuous case to the triangular shaded area, would be created. This excess **willingness** to pay is usually referred to as "**consumer's** surplus." [4/]

Panel B depicts the situation for the individual seller. The marginal cost curve indicates the incremental cost of producing additional units of the product. It can be thought of as a supply curve, indicating the amount of a good the seller would offer in the market at each price. The seller will offer additional units of a product only if price increases to compensate him for his additional costs. At price P_1^S he will offer one unit, at price P_2^S, two units, etc. If price P_N^S prevails in the market the seller can sell for $\left(P_N^S \cdot N\right)$, an amount of the product he would have been willing to sell for $\sum_i P_i^S$. In order to have this opportunity he would be willing to pay up to an amount equal to the surplus, $\left(P_N^S \cdot N\right) - \sum P_i^S$. This "producer's surplus", represented by the shaded area, can also be viewed as economic benefits.[5/]

Of course, all the consumers and producers of a particular good will interact in the market for the good. The aggregation of individual demands will create a market demand and the aggregation

of individual supplies will create a market supply; in a competitive market, price will be determined at the intersection of the demand and supply curves. Economic benefits in terms of the above discussion -- consumers' surplus plus producers' surplus -- can be measured as the shaded area in Figure I.2.

2. Technological Advance and Economic Benefits

Technological advance generates economic benefits by enabling society to get more from its given stock of resources. Since the definition of economic benefits employed in this study relies on valuations evidenced in market behavior, the measurement of benefits must concentrate on technological advance that has an impact on goods and services being sold in the market. There are two possible effects of such technological advance. One is to lower the costs of producing a good. This pushes the market supply curve to the right and increases the relevant area of consumers' and producers' surplus, as illustrated in Figure I.3, Panel A. The other possibility is the introduction of a new product, in which case the economic benefits are all those generated in the market for the product. Since new products are seldom completely new, it might be useful to think of the introduction of a new product as moving the supply curve from a position where the minimum price was higher than any consumer was willing to pay, down to a position where transactions were willingly consummated. The relevant area in this case is illustrated in Figure I.3, Panel B.[6]

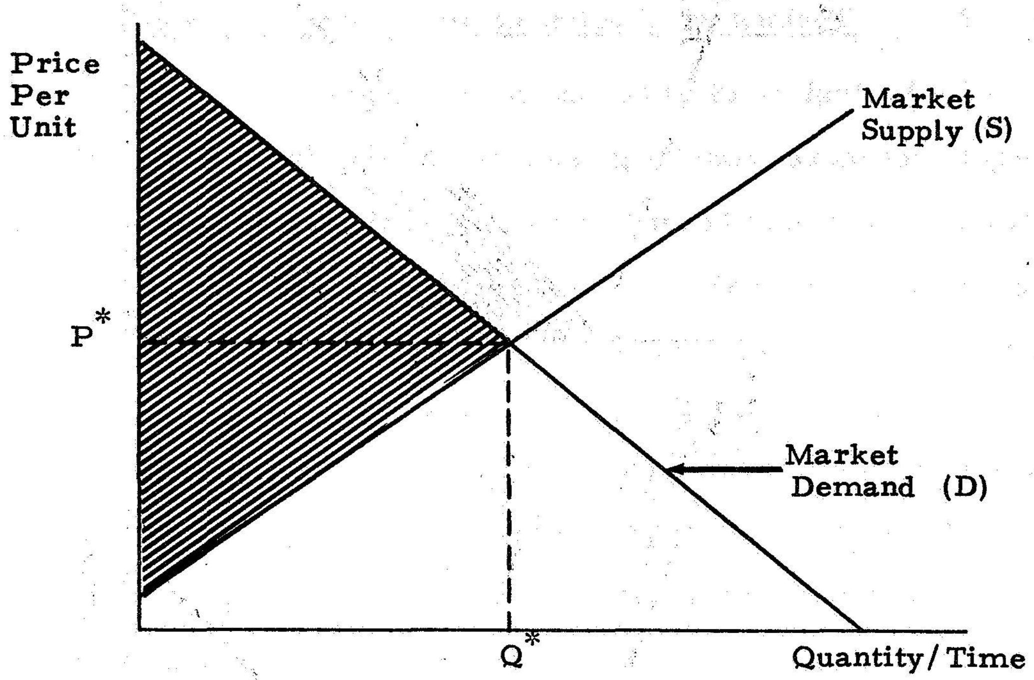

Price
Per
Unit
Market
Supply (S)
P*
Market
Demand (D)
Q*
Quantity/Time

Figure I.2

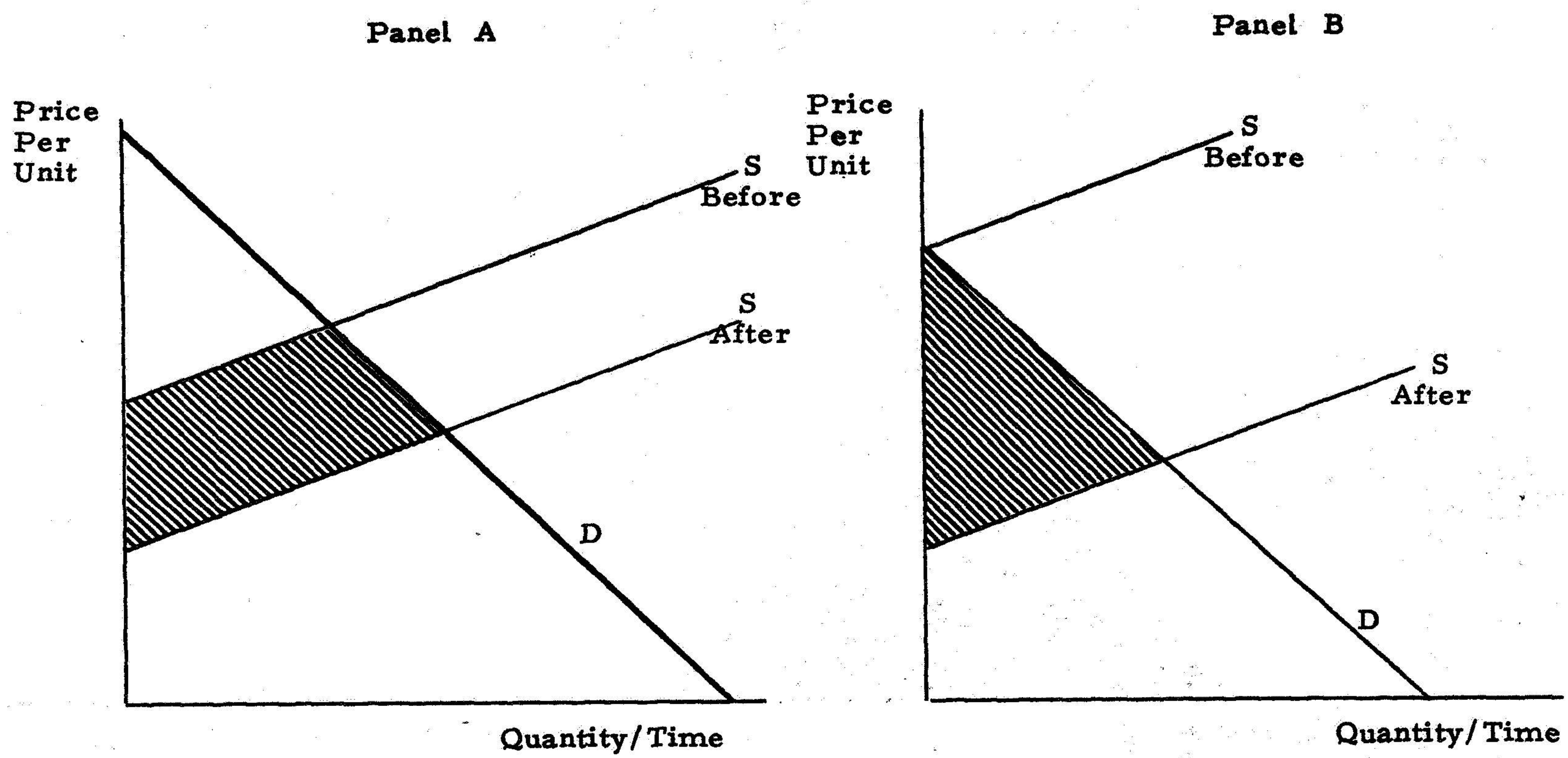
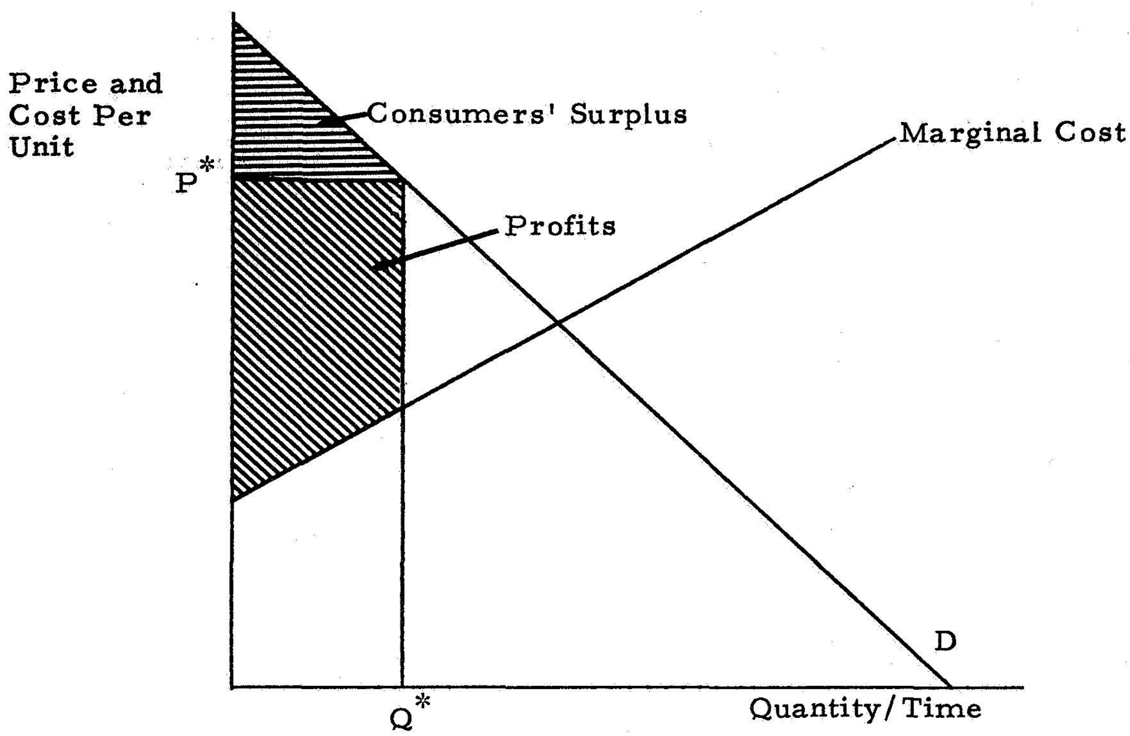

Panel A
Price
Per
Unit
S
Before
S
After
D
Quantity/Time
Panel B
Price
Per
Unit
S
Before
S
After
D
Quantity/Time

Figure I.3

3. Additional Considerations

Before proceeding futher, it would be useful to extend the simplified discussion above to consider two complications that can arise in applications of the suggested approach. First, the discussion above has so far assumed competition in the relevant markets. In fact, many markets are not competitive. In such cases, the market price does not occur at the intersection of the demand and supply curves. However, recalling the basic "willingness to pay" principle, economic benefits can still be assessed. Consider Figure I.4, which illustrates a market where the seller is a monopolist. Here the benefits are the sum of the consumers' surplus and profits, a surplus to the producer. The shaded area represents the maximum amount that consumers and the producer would be willing to pay rather than forego the sale of Q^* units at price P^*. In this case the benefits of a technological advance that reduces the monopolist's marginal costs would be the increment in consumers' surplus plus the increase in the producer's profits.

Consider now a second complication. Technological change often affects directly the prices of intermediate goods (i.e., goods used in the production of other goods) and through them the prices of final goods. The demand for the intermediate goods is a derived demand, based solely on their value in producing other final goods for consumption. Conceptually, consumers' surplus can only accrue to consumers of these final goods. As a result, measuring the benefits of a technological change which lowers the cost of an intermediate good can be more complex than is indicated by the simple illustration



Price and Cost Per Unit
Consumers' Surplus
Marginal Cost
P*
Profits
D
Q*
Quantity/Time

Figure I.4

above. Specifically, if an innovation lowers the cost of an intermediate good, its economic benefits, as defined above, would be the sum of: (1) the increase in consumers' surplus in the markets for final goods which use the intermediate good as an input, and (2) the increased profits which accrue to producers.

In the extreme, of course, the intermediate good may be "intermediate" to only one final good and, thus, affect only one market. In this case the measurement of benefits would be straightforward. However, in cases where many final good markets are affected, the measurement of these benefits would seem to be an extremely involved task requiring the calculation of benefits accruing in all of these final good markets. Fortunately, however, the benefits that accrue in the form of consumers' surplus in the various final good markets can be approximated using data on demand and cost relationships in the intermediate market. This result obtains because of the relationship between derived demand for an intermediate product (innovation) and demand in final good market(s). A complete exposition of how this relationship affects benefits calculations is presented in an appendix to this text.

C. Methods of Measuring the Economic Benefits of Technological Advance

Actual and precise measurement of the relevant economic benefits requires detailed knowledge of the cost and demand curves for a product before and after a technological advance. In order to simplify

the measurement process, two working assumptions, both of which impart a downward bias to our estimates, will be employed throughout most of the study. The first is that average cost and supply curves are horizontal. The second is that cost savings are a good approximation of the change in consumers' and producers' surplus.

It should be noted that the second working assumption has somewhat different implications for competitive and non-competitive markets. Consider first the case illustrated in Figure I. 5, where the supply curve of a competitive industry has shifted down from S_0 to S_1, price has fallen from P_0 to P_1, and quantity has increased from Q_0 to Q_1. The relevant shaded area of economic benefits in Figure I. 5 is approximately equal, for small changes in P, to

$$(P_0 - P_1)\, Q_1\, (1 - 1/2k\eta) \tag{I. 1}$$

where $k = \dfrac{P_0 - P_1}{P_1}$ and η is the mean absolute value of the price elasticity of demand over the range P_0 to P_1.

Note that if k, the proportional change in price, is small, the estimate is fairly insensitive to values of η. In practice, therefore, rather imprecise knowledge of the demand curve is adequate to make reasonably accurate estimates in most cases. Where the fall in price is relatively large, however, as with the introduction of a new product, accurate knowledge of the demand relationship becomes essential.

Since Q_1 is generally directly observable, the principal task will be the determination of the change in price generated by technological advance. Because, in the competitive environment assumed, price equals

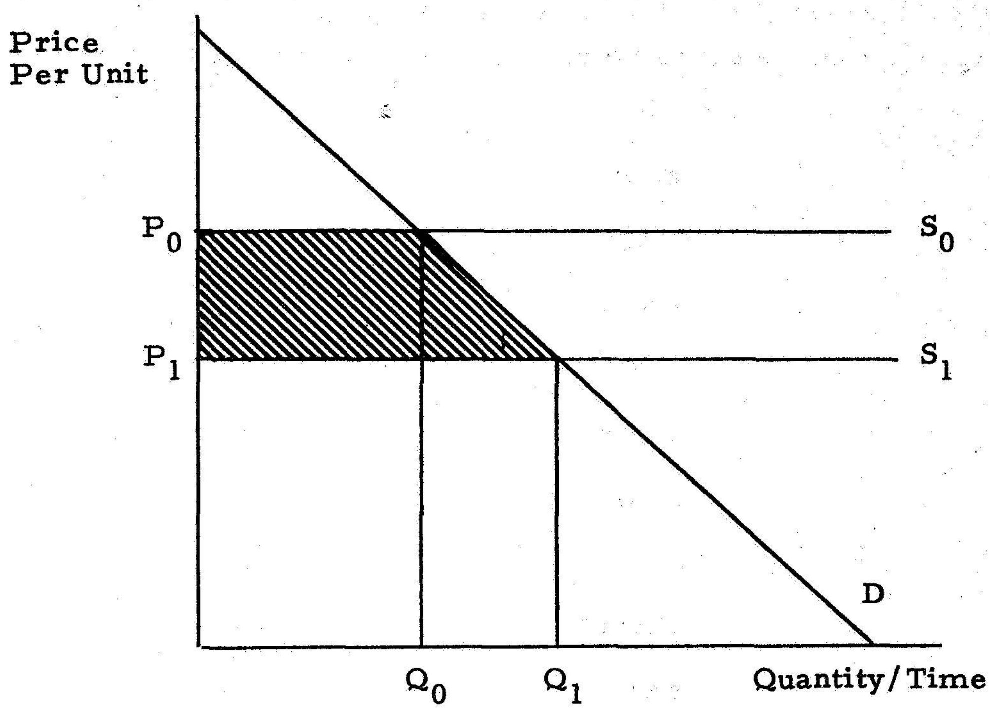


Figure I.5

average cost, the problem can alternatively be viewed as one of determining the resulting change in costs of production.

Figure I.6 illustrates the case of a cost reduction in a non-competitive industry characterized by constant average costs. Initially the sum of consumers' and producers' surplus is area ZRST . (The marginal revenue curve is not shown because it complicates the diagram.) When the average cost curve shifts from AC_0 to AC_1 , the sum of consumers' and producers' surplus becomes ZUVW, with a change equal to the shaded area RUVWTS. To the extent that cost savings are passed on to the consumer in terms of lower prices (which depends on the price elasticity of demand), there will be some redistribution of benefits between producers and consumers.

Note that a conservative approximation of benefits could be obtained by simply measuring the cost savings represented by $(AC_0 - AC_1)Q_1$. This approach has in fact been adopted in the present analysis because of the difficulties in obtaining profit data.[7/] Thus, the problem is reduced to one of measuring changes in costs induced by technological innovation. Since a myriad of specific methods are possible, and since the appropriate choice will depend on the particulars of the case under consideration, a discussion of precise specifications is left to the case study chapters where they are employed.

D. Methods for Assessing Benefits Due to NASA

The research process by which technological advances are generated typically involves a complex interaction of various groups and individuals. In solving the particular problems associated with

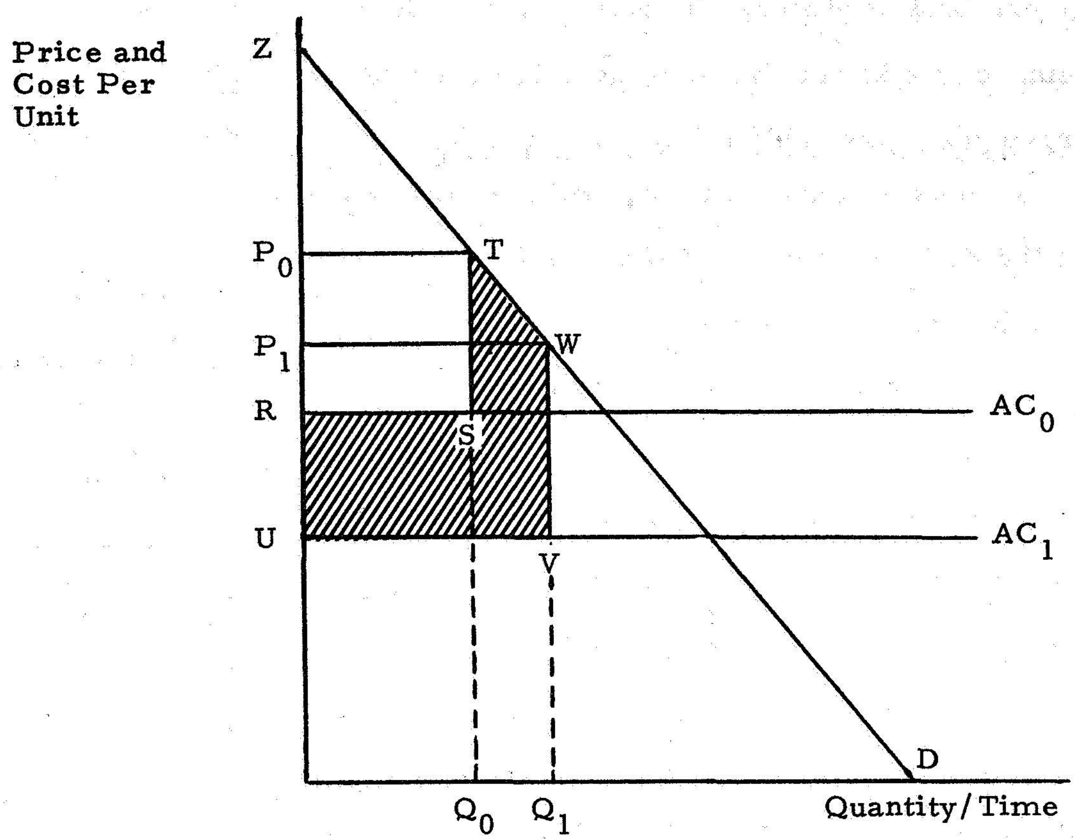

Price and
Cost Per
Unit
Z
P0
T
P1
W
R
S
AC0
U
AC1
V
D
Q0
Q1
Quantity/Time

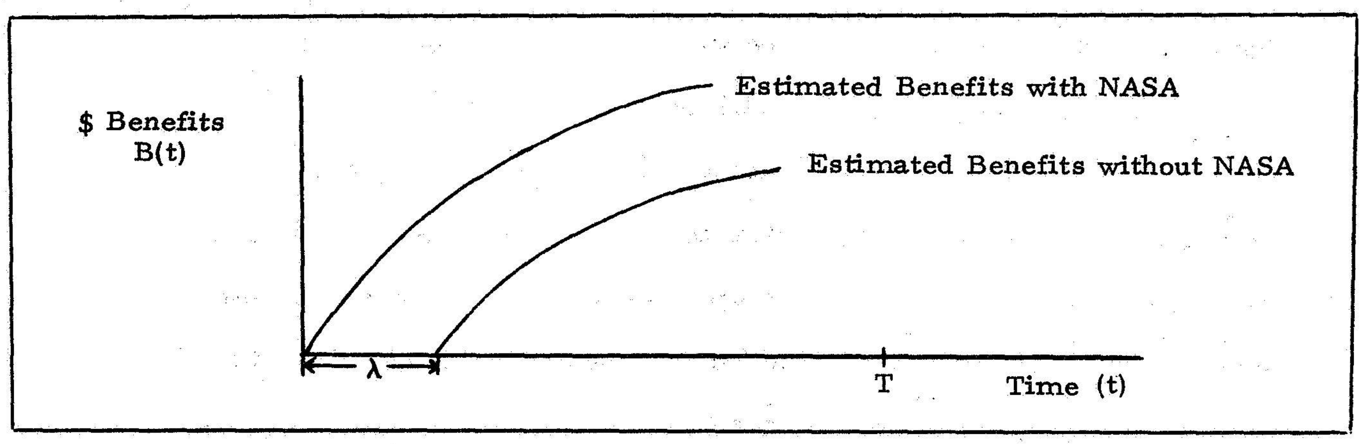
Figure I. 6

an advance, the individual research "actors" build on or combine their results with those generated by others. As a result, any "credit" for the benefits created by a particular advance should in a real sense be shared by the various contributors.

The goal here, of course, is to assign some particular share in some particular cases to NASA. The method for assigning this share is based on the premise that NASA R&D led to an earlier realization of the particular technological advances being considered. In other words, had NASA not participated in the R&D process -- and had its failure to do so not led to changes in R&D by others -- these technological advances would indeed have occurred, but at a later date.[8/]

If one accepts this view of how technological advance is generated -- and it has been proposed and defended by a number of authors[9/] -- then the measurement of benefits attributable to NASA becomes, at least theoretically, a rather straightforward task. These benefits can be measured as the difference between the present value of two benefits streams: one, the stream resulting from the advance as it has occurred; and two, the stream that would have resulted had NASA not been involved. These two streams may differ in complex ways. One might, of course, conceive of a very simple case, illustrated in Figure I. 7, where NASA's contribution is in the difference in the present value of two identical streams starting at different dates. More realistically, the streams may not be identical. For one thing, the benefits generated depend both on the nature of the

Figure I.7



$$\text{NASA Benefits} = \int_0^T B(t)e^{-rt}dt - \int_0^T B(t-\lambda)e^{-rt}dt$$

where r = the discount rate

advance and on the perhaps changing external environment. This environment affects demand for goods and services whose production and consumption may also be influenced by the advance. For another thing, the acceleration due to NASA may not be a one-time acceleration, but rather a set of such affects occurring at different points.

As a practical approach, the study allows the benefits streams to differ due to cost and demand considerations, but assumes that NASA's contribution results in a one-time "speed-up." One way to determine this speed-up is to ask "experts" to judge this reduction in development time due to NASA. (By "**experts**" are meant people with expertise in, and intimate acquaintance with, the evolution of the technologies involved.) A more formal approach might involve reiterating the initial opinions among the experts and asking for revised opinions -- an application of the so-called "Delphi" technique. However, the "Delphi" method was not used in this study. Rather, in the sequence of empirical studies documented in the following chapters, estimates of benefits were made using various alternative "speed-up" values from ranges of expert opinions elicited in a one-time survey. In order to give some perspective on these opinions, brief summaries of major technological developments are provided in each case study technological area.

E. Outline of Succeeding Chapters

The chapters that follow represent the results of the preliminary application of the methods outlined above. Chapters II through V

present estimates of the economic benefits of NASA technology for four cases of secondary applications where NASA involvement has been generally recognized as important. These are: cryogenic multilayer insulation, gas turbines in electric power generation, integrated circuits, and NASTRAN, a NASA program for computer assisted structural analysis.

Each of the case study chapters follows the same general format. It begins with an introductory section which briefly describes the nature of the technology and the benefits generated. Then the method of estimating total benefits of the technological advance is described and implemented. Finally, after a descriptive discussion of NASA's role in the field and a presentation of expert estimates of NASA's specific "speed-up" role, a range of possible benefits due to NASA are presented.

The calculations of benefits are in terms of the present discounted values in 1974 of a stream of benefits over two periods. The first period ranges from the onset of the innovation up to 10 years from the last year for which data were available; the second ranges from the onset of the innovation into perpetuity.

Chapter VII of the monograph summarizes and puts into perspective the material preceding it. The various techniques and the results of their implementation are appraised and the implications of the findings are discussed.

FOOTNOTES - CHAPTER I

1. National Aeronautics and Space Act of 1958.

2. For some examples, see the annual Program Reports of NASA's Technology Utilization Office.

3. It should be noted that the concept of benefits employed here has been the subject of controversy. However, as most everyone admits, such concepts are the only practical tools for applied work of this sort. See, for example, J. Currie, J. Murphy, and A. Schmitz, "The Concept of Economic Surplus and Its Use In Economic Analysis," Economic Journal, December 1971; and A.C. Harberger, "Three Basic Postulates for Applied Welfare Economics: An Interpretive Essay," Journal of Economic Literature, September 1971.

4. To be conceptually correct, this demand curve should be an "income compensated" demand curve, i.e., one along which real income is held constant. In practice, the difference in the shaded area measured from compensated and uncompensated demand curves is likely to be insignificant. For more on this point see E.J. Mishan, Cost-Benefit Analysis, New York: Praeger, 1971.

5. For some further discussion of what "producers' surplus" is, see J.M. Currie, et. al., op. cit., and E.J. Mishan, "What is Producers' Surplus," American Economic Review, December 1968.

6. It should be noted that this and succeeding discussions ignore any secondary effects that such a change might bring about in other markets.

7. Of course, even if such data were obtainable, they would in all likelihood refer to "accounting profits" which, since they include returns to certain factors of production, tend to overstate true "economic profits."

8. Two points should be emphasized. One, by technological advance is meant all new or improved products or processes. Therefore, if NASA's contribution led to better quality, this better quality would have been achieved at some later date. Two, it is possible that NASA's contribution is so significant that the acceleration due to NASA approaches infinity.

9. See, for example, I.C.R. Byatt and A.V. Cohen, An Attempt to Quantify the Economic Benefits of Scientific Research, Science Policy Studies, London: Her Majesty's Stationery Office, 1969; and A.W. Brown, "The Economic Benefits to Australia From Atomic Absorption Spectroscopy," Economic Record (June 1969); and F.M. Scherer, "Quantifying the Economic Benefits of NASA-Originated Technology," mimeo, April 21, 1971.

CHAPTER II:

CRYOGENIC MULTILAYER INSULATION

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A. Introduction

1. Brief Description of Technology

NASA's role in cryogenic technology is an outgrowth of the effort to minimize the weight, volume, and evaporation loss of gases used in launch and flight propulsion systems, life support systems, and power generation on board spacecraft. Much greater efficiency is possible if these gases, primarily oxygen, hydrogen, and helium, are stored as cryogenic liquids (i.e., liquids with boiling points well below 0^{o}F) rather than as gases under high pressure. Because NASA's requirements exceeded the available technology, a great deal of research and development was undertaken under NASA auspices. NASA's general research objectives included the development of new insulation systems; investigation of the thermophysical properties of a wide range of materials; development of new equipment for producing, storing, and transporting large quantities of cryogens; and the construction of analytical models and data applicable to many facets of cryogenic technology. Many of these efforts have already found commercial applications; the one which is examined here is the development of multilayer reflective superinsulation materials.

By the beginning of the space program, two types of multilayer insulation had become commercially available, but they were judged inadequate by NASA because they were fragile, variable in performance, difficult to apply, and subject to relatively underdeveloped manufacturing

and application techniques. NASA, therefore, became interested in developing new insulations and more sophisticated fabrication and application systems. The development of this technology contributed substantially to the rapid growth of the cryogenics industry. The resulting ease and efficiency of producing, storing, and transporting cryogenic liquids have led to benefits in such diverse areas as cryosurgery, preservation of biomedical materials, food preservation, superconductivity, steel manufacturing, and cryometallurgy. It has also facilitated the production of a number of new consumer products.

The function of insulation is to retard the flow of energy from a region of high energy to a region of low energy. Cryogens represent a region of extremely low thermal energy and must, therefore, be well insulated; otherwise, they will "boil off" or evaporate. The efficiency of the insulation depends on a number of factors, including the type of cryogen stored, the temperature difference between the cryogen and the environment outside the tank, the type of insulation material, and its thickness. Since, in general, a cryogenic liquid will eventually boil off regardless of the type or thickness of the insulation, consideration must be given to the length of time the cryogen is typically held.

2. Nature of Benefits Generated

Multilayer insulation was developed because of the requirements to hold two specific cryogens, helium and hydrogen, longer than any other bulk type insulation of feasible thickness could hold them. Multilayer insulation is at least 20 times more effective than and one-sixth as dense as perlite, its nearest competitor. [1/]

Although its cost is 20 percent more than that of perlite, it has proven to be cheaper for some applications. [2/]

This chapter presents estimates of the benefits which result from the use of multilayer insulation for tanks which are used to transport liquid hydrogen, liquid helium, and liquid nitrogen. The tanks are filled, loaded on trucks, and, if necessary, can be transferred to ships to be further transported. It should be emphasized that other benefits arise from the use of multilayer insulation at various stages in the production and marketing of these cryogens. For example, it is used to insulate storage tanks, piping, and other equipment used in the fabrication process. In addition, multilayer insulation has many applications in other goods and services. Unfortunately, it has not been possible to determine the extent of these benefits. Therefore, the estimates of benefits presented herein should be viewed as representing only a part of the total benefits arising from the development of multilayer insulation technology.

B. Measurement of Benefits

1. Methods Applied

The method applied in analyzing the benefits of multilayer superinsulation material involves estimating the increase in costs that would occur if the next best insulator, perlite, were used in its place in the transport of liquid hydrogen, liquid helium, and liquid nitrogen. There are two factors that would cause costs to increase if perlite were used in place of multilayer insulation:

(i) Because multilayer superinsulation of a given thickness used in a vacuum annulus is many times more efficient than perlite in retarding heat transfer, less cryogen will boil off per unit time in a tank insulated with the multilayer material, other things being equal. Thus, in order to deliver a given quantity of cryogen, a shift from multilayer to perlite would necessitate a greater level of production and, therefore, entail higher costs and commitment of more resources per unit delivered.

(ii) Because multilayer superinsulation weighs much less than perlite, the cost of transporting a tank of given volume is lower with multilayer. Again, a shift from multilayer to perlite would cause the unit cost of cryogens to increase

The cost differences resulting from the use of these two insulations can be expressed symbolically. Let

X	=	the quantity of cryogen delivered
B^j	=	the amount of evaporation loss (boiloff) while the cryogen is in the transport tank; $j = p$ if the tank is insulated with perlite, and $j = m$ if insulated with multilayer
$X + B^j$	=	the amount of cryogen that must be produced with insulation j in order to deliver quantity X
$C^j(Y)$	=	the cost of producing quantity Y with insulation j.

If it is assumed that production costs per unit of cryogen are the same regardless of the type of insulation,

$$C^p(X) = C^m(X) = C(X) \tag{II.1}$$

It is known that $B^p > B^m$; therefore, assuming constant unit costs,

$$C(B^p) > C(B^m) \tag{II.2}$$

$$C(X + B^p) > C(X + B^m) \tag{II.3}$$

$$\Delta C = C(X + B^p) - C(X + B^m) \tag{II.4}$$

$$\Delta C = C(X) + C(B^p) - C(X) - C(B^m) \tag{II.5}$$

$$\Delta C = C(B^p - B^m) = C\Delta B \tag{II.6}$$

where ΔB is the difference in the amount of boiloff between perlite and multilayer insulation.

Since the total cost difference consists of the difference in production costs plus the difference in transport costs, let

$T^j(Y)$ = the cost of transporting quantity Y with insulation j and assume constant unit costs. Then,

$$\Delta T = T^p(X + B^p) - T^m(X + B^m) \tag{II.7}$$

Since $B^p = B^m + \Delta B$,

$$T^p(X + B^p) = T^p(X + B^m + \Delta B) \, , \tag{II.8}$$

and substituting (II.8) into (II.7) yields

$$\Delta T = T^p(X + B^m + \Delta B) - T^m(X + B^m) \tag{II.9}$$

The combined effect of ΔC and ΔT is to shift the cost curve up as a change is made from multilayer to perlite. An estimate is made of the upward shift in the cost curve that would occur if multilayer reflective superinsulation were withdrawn from the market and perlite substituted in its place. Suppose that the cryogen-producing industry is competitive and faces constant unit costs. Then the industry supply curve is perfectly elastic (Figure II.1) and coincides with the average cost curve. 3/

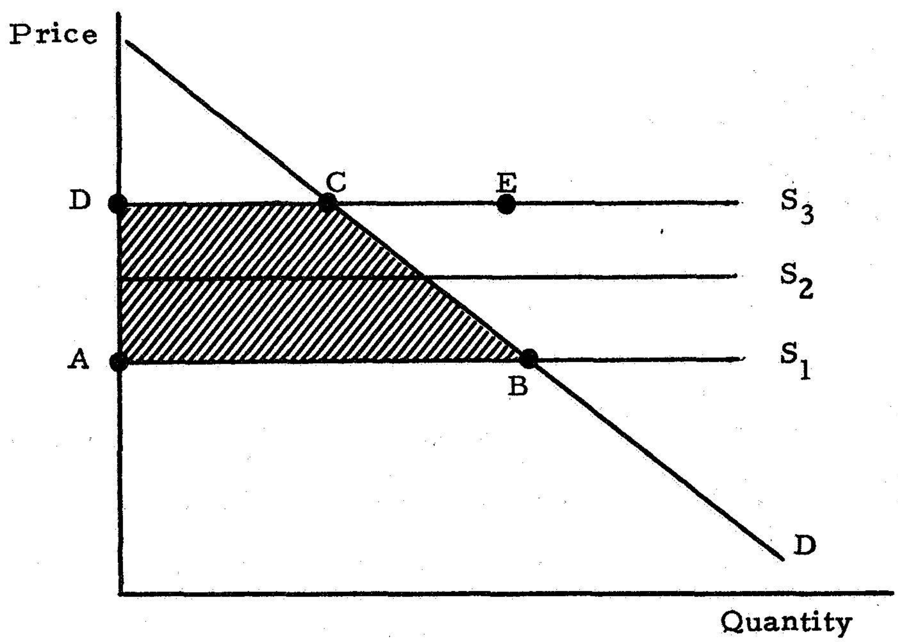


Figure II. 1

In the shift from multilayer to perlite, the increase in boiloff rates is equivalent to a reduction in productivity and the supply (average cost) curve shifts from S_1 to S_2. An increase in transportation costs resulting from heavier insulation material (and the increased quantity that must be transported) causes an additional upward shift to S_3. Consumers' surplus will decrease by area ABCD. Thus, the use of multilayer superinsulation materials benefits the economy, in terms of consumers' surplus, to the extent of area ABCD.

The actual computation of the benefits (S) of multilayer reflective superinsulation over its next best substitute, perlite, is based on equations (II. 6) and (II. 9) above:

$$S = \Delta C + \Delta T \qquad \text{(II. 10)}$$

$$S = C\Delta B + T^p(X + B^m + \Delta B) - T^m(X + B^m) \qquad \text{(II. 11)}$$

When rearranged, these become:

$$S = C\Delta B + (T^p - T^m)X + (T^p - T^m)B^m + T^p\Delta B \qquad \text{(II. 12)}$$

$$S = (C + T^p)\Delta B + (T^p - T^m)(X + B^m) \qquad \text{(II. 13)}$$

The first term in the right-hand side of equation (II. 13) will be referred to as boiloff savings and the second term as transportation savings.

Boiloff savings were computed by calculating the amount of cryogen that boils off while in the transport tank insulated with perlite or multilayer, and then multiplying the difference by the sum of production and transporta-

tion costs. Since explicit cost figures are not available, the price of the cryogen was taken as a proxy for costs: in a competitive market, price and costs are expected to be relatively close. The computational procedure, then, is as follows:

$$\text{Boiloff savings} = \text{production} \times \text{differential boiloff rate} \times \text{time in transport tank} \times \text{price}$$

Production of each cryogen was calculated by multiplying the total production of hydrogen, helium, or nitrogen by an estimate of the proportion of the total that is produced in liquid form. The differential boiloff rate was obtained from information concerning the relative efficiency of perlite and multilayer insulation and the proportional relationship between thermal conductivity and boiloff rates. Time and price statistics were supplied by industry and published sources, respectively.

In order to compute transportation savings, the level of production $(X + B^m)$ was multiplied by the difference in unit transportation costs under conditions of multilayer and perlite insulation. Since this cost difference is caused by the fact that perlite is heavier than multilayer insulation, $(T^p - T^m)$ was obtained as follows in the case of liquid hydrogen and liquid nitrogen:

$$(T^p - T^m) = [\text{number of trucks} \times \text{number of trips/truck/year} \times \text{cost/ton-mile} \times \text{average number of miles/trip} \times \text{weight difference}] - [\text{number of trucks} \times \text{difference in annual depreciation/truck}].$$

For liquid helium, the same procedure was used, except that savings in shipping costs were added to savings in trucking costs for that part of total production that is exported:

$$\text{Shipping savings} = \text{number of tank loads exported} \times \text{cost/ton-mile} \times \text{average number of miles shipped} \times \text{weight difference per tank}.$$

The number of trucks and tank loads was obtained from the assumption that all liquid hydrogen, helium, and nitrogen is shipped in a standard 11,000 gallon tank, and assumptions concerning the number of trips a truck can be expected to make per year. The average number of miles per trip was an estimate based on conversations with industry sources, and the costs per ton-mile for trucking and shipping were obtained from sources in those industries. The weight difference per tank was calculated for the standard size tank, based on information on the density of the insulation material and assumptions about the thickness of the insulation. The difference in depreciation was netted out to reflect the fact that, although maintenance and inspection costs are roughly the same for both types of insulation, multilayer is more expensive. The difference in design costs

(a one-time expense) [4] was also subtracted out from the first year's savings.

Total benefits were computed for each year from 1960 to 1973 and were expressed in terms of 1974 prices. Each year's figure was then multiplied by the appropriate discount factor to obtain the present value of the stream of benefits from 1960 to 1973. A similar procedure was then followed to project the stream of benefits for the next ten years. [5]

It might be noted that the estimate of benefits of relective superinsulation materials presented here is biased downwards in at least two respects. First, the estimates do not reflect any savings that take place during production or storage. Second, the estimates deal with only one application of a material that has many more uses. For example, reflective superinsulation materials are also used for the insulation of liquid oxygen and certain rare gases like xenon and krypton. Also, current "best practice" cryogenic piping uses superinsulation, and variations of the materials have been adapted for use in products such as ski jackets, sporting equipment, survival kits, thermal window shades, and window coatings.

2. <u>Data Sources</u>

The data underlying the computations and assumptions of this analysis were obtained from a wide variety of sources. Whenever available, published sources were used; these include both industry and government publications. Other information was obtained by personal or telephone interviews with industry and government personnel. A complete list of references is given in an appendix to the text.

3. Results of Estimates and Calculations of Total Benefits

Table II. 1 presents a summary of the annual calculations for hydrogen, Table II. 2 for helium, and Table II. 3 for nitrogen. These follow the steps outlined in Section B. 1 of this chapter for calculating the cost savings due to reduced boiloff loss and lower transportation costs when multilayer is used instead of perlite.[6/]

The present value of the 1960-1983 stream of benefits attributable to the use of multilayer insulation instead of perlite is $2.1 billion if a 5 percent discount rate is assumed, and $2.2 billion if the discount rate is 10 percent. The corresponding figures for helium are $531 million and $567 million; for nitrogen they are $61 million and $64 million; and for hydrogen they are $1,535 million and $1,542 million.

C. Assignment of Benefits to NASA

1. Chronology of Developments

The origins of the cryogenics industry date back to the end of the last century, and liquid oxygen was produced commercially in both Europe and America in the first decade of the twentieth century. From its beginning, the industry was faced with the difficulty of storing gases at cryogenic temperatures for more than a few days. The Dewar vessel, which has a double wall separated by a vacuum and coated with a silvered reflective surface, was traditionally used for the storage and transportation of cryogenic substances. However, the amount of heat loss sustained, even in short periods, was very great. The Dewar vessel was, consequently, unsuitable for the storage of hydrogen and helium in more than laboratory quantities.

Table II. 1 - Hydrogen

Year	Production (Billion Cu. Ft.)	Proportion Liquified	Net Production[1] (Billion Cu. Ft.)	Price[2] Per Cu. Ft.	Boil-Off Savings[3] ($Thousands)	Quantity[1] (Million Gallons)	Number of Trucks	Trucking Cost[2] Per Ton-Mile	Design and Depreciation Differential[2]	Transportation Savings[4] ($Thousands)	Total[5] Benefit 1974 Prices ($Thousands)	Net Benefit[6] 1974 Prices ($Thousands)	Discounted[7] Net Benefit ($Thousands)	Discounted[8] Net Benefit ($Thousands)
1960	644	.0003	.08	.0432	539	0.6	1	.088	458	12	551	510	1,010	1,938
1961	723	.0015	.51	.0418	3,398	4.2	3	.089	249	37	3,435	3,157	5,967	10,892
1962	814	.0026	.96	.0410	6,311	7.9	5	.089	415	62	6,373	5,858	10,544	18,394
1963	911	.0054	2.22	.0400	14,253	18.2	11	.092	913	140	14,393	13,230	22,623	37,706
1964	1007	.0060	2.77	.0390	17,304	22.7	13	.092	1,079	166	17,470	16,059	26,176	41,593
1965	1155	.0092	4.86	.0379	29,453	39.7	23	.090	1,909	287	29,740	27,338	42,374	64,518
1966	1500	.0089	6.04	.0365	35,291	49.4	29	.085	2,407	342	35,633	32,755	48,477	70,096
1967	1880	.0067	6.14	.0353	34,656	50.1	29	.088	2,407	354	35,010	32,181	45,375	62,753
1968	2060	.0067	6.30	.0338	34,081	51.5	30	.090	2,490	374	34,455	31,668	42,435	56,052
1969	2163	.0067	9.49	.0315	47,840	77.6	45	.091	3,735	586	48,408	44,489	56,946	71,627
1970	2340	.0067	12.99	.0306	63,579	106.1	61	.092	5,063	778	64,367	59,154	72,168	6,365
1971	2580	.0067	15.75	.0302	76,094	128.7	74	.093	6,142	954	75,140	69,204	80,277	92,041
1972	2700	.0067	17.51	.0296	82,942	143.1	81	.092	6,723	1,033	81,909	75,438	82,982	91,280
1973	2800	.0067	18.38	.0296	87,024	150.2	86	.094	7,138	1,121	88,145	81,003	85,053	89,103
1974	3057	.0067	20.48	.0296	96,907	167.4	96	.094	7,968	1,251	98,158	90,212	90,212	90,212
1975	3242	.0067	21.72	.0296	102,771	177.5	101	.094	8,383	1,316	104,087	95,662	91,107	86,965
1976	3428	.0067	22.97	.0296	108,668	187.7	107	.094	8,881	1,394	110,062	101,153	91,957	83,598
1977	3613	.0067	24.21	.0296	114,532	197.9	113	.094	9,379	1,473	116,005	106,614	91,090	80,101
1978	3800	.0067	25.46	.0296	120,460	208.1	119	.094	9,877	1,551	122,011	112,134	91,913	76,804
1979	3985	.0067	26.70	.0296	126,324	218.2	124	.094	10,292	1,616	127,940	117,584	91,863	73,034
1980	4172	.0067	27.95	.0296	132,252	228.4	130	.094	10,790	1,694	133,946	123,104	91,879	69,440
1981	4357	.0067	29.19	.0296	138,117	238.6	136	.094	11,288	1,772	139,889	128,565	91,181	65,931
1982	4543	.0067	30.44	.0296	133,013	248.8	142	.094	11,786	1,851	145,864	134,057	90,579	62,643
1983	4730	.0067	31.69	.0296	149,941	259.0	148	.094	12,284	1,929	151,870	139,576	90,049	59,142
													1,535,046	1,542,398

[1] Total liquified production less NASA purchases
[2] Prices expressed in 1974 dollars
[3] Based on differential boil-off = .16
[4] Based on weight differential = 1.09 T.
[5] Totals may differ from sum of components because of rounding
[6] Total benefit less triangle area (see Fig. II.1)
[7] Discount rate = 5%
[8] Discount rate = 10%

Table II. 2 - Helium

Year	Production (Million Cu. Ft.)	Proportion Liquified	Price[1] Per Cu. Ft.	Boil-Off Savings[2] ($Thousands)	Quantity (Thousand Gallons)	Number of Trucks	Trucking Cost[1] Per Ton-Mile	Design & Depreciation Differential[1]	Exports (Million Cu. Ft.)	Number of Tank Loads	Shipping Cost[1] Per Ton-Mile	Transportation Savings[3] ($Thousands)	Total[4] Benefit 1974 Prices ($Thousands)	Net[5] Benefit 1974 Prices ($Thousands)	Discounted Net Benefit[6] ($Thousands)	Discounted Net Benefit[7] ($Thousands)
1960	642	.05	.050	1,422	319	1	.088	458	0	0	-	29	1,451	793	1,570	3,013
1961	728	.05	.050	1,613	362	1	.089	83	0	0	-	30	1,643	901	1,703	3,108
1962	713	.05	.050	1,579	354	1	.089	83	0	0	-	30	1,609	883	1,589	2,773
1963	2231	.05	.050	4,942	1,108	2	.092	166	0	0	-	61	5,003	2,759	4,718	7,863
1964	4027	.05	.050	8,920	2,001	3	.092	249	0	0	-	92	9,012	4,978	8,114	12,893
1965	4365	.05	.050	9,475	2,169	4	.090	332	12.6	12	.026	124	9,599	5,291	8,201	12,487
1966	4606	.11	.047	21,098	5,034	8	.085	664	39.2	36	.026	238	21,336	11,778	31,578	45,659
1967	4712	.16	.047	31,395	7,491	11	.088	913	49.8	45	.027	337	31,732	17,524	24,709	34,172
1968	4855	.21	.046	41,553	10,131	15	.090	1245	65.0	59	.027	469	42,022	23,196	31,083	41,057
1969	4662	.29	.044	52,706	13,434	20	.091	1660	90.0	82	.026	632	53,338	29,426	37,665	47,376
1970	4600	.34	.043	59,585	15,541	23	.092	1909	105.0	95	.027	736	60,321	33,269	40,588	48,573
1971	4560	.42	.041	69,572	19,030	28	.093	2324	130.0	118	.028	908	70,480	38,850	45,066	51,670
1972	4094	.45	.024	39,175	18,306	26	.092	2324	138.0	125	.027	838	40,013	21,908	24,099	26,509
1973	3205	.50	.034	48,274	15,923	23	.094	2324	161.1	146	.028	769	49,043	26,971	28,320	29,668
1974	3205	.57	.030	48,558	18,158	26	.094	2324	184.8	168	.028	870	49,428	27,139	27,139	27,139
1975	3205	.58	.030	49,750	18,598	27	.094	2324	208.2	190	.028	909	50,659	27,807	26,483	25,279
1976	3205	.60	.030	50,943	19,044	28	.094	2324	231.6	211	.028	947	51,890	28,475	25,886	23,533
1977	3205	.61	.030	52,136	19,490	28	.094	2324	255.0	232	.028	953	53,089	29,140	25,121	21,910
1978	3205	.63	.030	53,328	19,936	29	.094	2407	278.4	254	.028	991	54,319	29,809	24,434	20,417
1979	3205	.64	.030	54,521	20,382	29	.094	2407	301.8	275	.028	998	55,519	30,474	23,808	18,928
1980	3205	.65	.030	55,714	20,827	30	.094	2490	325.2	296	.028	1037	56,151	31,142	23,240	17,394
1981	3205	.67	.030	56,906	21,273	31	.094	2573	348.6	317	.028	1075	57,981	31,810	22,560	16,313
1982	3205	.68	.030	58,099	21,719	31	.094	2573	372.0	339	.028	1082	59,181	32,475	21,943	15,175
1983	3205	.70	.030	59,291	22,165	32	.094	2656	395.4	360	.028	1120	60,441	33,144	21,383	14,044
															531,000	567,153

[1]Prices expressed in 1974 dollars.

[2]Based on differential boiloff = .886

[3]Based on weight differential = 3.27 T.

[4]Totals may differ from sum of components because of rounding.

[5]Total benefit less triangle area (see Fig. II.1).

[6]Discount rate = 5%

[7]Discount rate = 10%

Table II. 3 - Nitrogen

	Production[1] (Billions Cu. Ft.)	Price[2] Per Thousand Cu. Ft.	Boil-Off Savings[3] ($ Thous.)	Quantity (Million Gallons)	Number of Trucks	Trucking Cost[2] Per Ton-Mile	Design & Depreciation Differential[2]	Transport. Savings[4] ($ Thous.)	Total[5] Benefit 1974 Prices ($ Thous.)	Net Benefit[6] 1974 Prices ($ Thous.)	Discounted[7] Net Benefit ($ Thous)	Discounted[8] Net Benefit ($ Thous.)
1960	.84	$2.20	$13.9	9.0	6	$.089	873	$430	$444	$391	$774	$1486
1961	1.05	2.20	17.3	11.3	7	.089	581	502	519	461	871	1590
1962	1.41	2.20	23.3	15.2	9	.090	747	652	675	602	1084	1890
1963	1.65	2.20	27.2	17.7	11	.092	913	815	842	744	1272	2120
1964	2.14	2.19	35.1	23.0	14	.092	1162	1037	1072	949	1547	2458
1965	2.71	2.28	46.3	29.1	17	.090	1411	1232	1278	1146	1776	2705
1966	3.16	2.21	52.4	33.9	20	.085	1660	1369	1421	1276	1888	2731
1967	3.89	2.57	75.0	41.8	24	.088	1992	1701	1776	1618	2281	3155
1968	4.48	2.69	90.4	48.1	28	.090	2324	2030	2120	1934	2592	3423
1969	4.68	2.43	85.3	50.3	29	.091	2407	2126	2211	1996	2555	3214
1970	5.22	2.23	87.3	56.1	32	.092	2656	2371	2458	2198	2682	3209
1971	5.31	2.00	79.6	57.0	33	.093	2739	2472	2552	2245	2604	2986
1972	5.90	1.77	78.3	63.4	36	.092	2988	2668	2746	2385	2624	2886
1973	6.66	1.75	87.4	71.5	41	.094	3403	3104	3191	2754	2892	3029
1974	7.19	1.75	94.4	77.2	44	.094	3652	3332	3426	2960	2960	2960
1975	7.77	1.75	102.0	83.5	48	.094	3984	3634	3736	3223	3070	2930
1976	8.39	1.75	110.1	90.1	52	.094	4316	3937	4047	3489	3172	2883
1977	9.06	1.75	118.9	97.3	56	.094	4648	4240	4359	3760	3241	2827
1978	9.79	1.75	128.5	105.2	60	.094	4980	4543	4671	4034	3307	2763
1979	10.57	1.75	138.7	113.5	65	.094	5395	4922	5061	4369	3413	2714
1980	11.41	1.75	149.8	122.6	70	.094	5810	5300	5450	4706	3512	2659
1981	12.33	1.75	161.8	132.4	76	.094	6308	5755	5917	5106	3621	2618
1982	13.31	1.75	174.7	143.0	82	.094	6806	6209	6384	5509	3722	2574
1983	14.38	1.75	188.7	154.5	88	.094	7304	6663	6852	5919	3819	2508
											61279	64318

[1]Includes only production shipped in multilayer tanks = 10 percent of total.
[2]Prices expressed in 1974 dollars.
[3]Based on differential boil-off = .0075.
[4]Based on tonnage differential = 6.31T.
[5]Totals may differ from sum of components because of rounding.
[6]Total benefit less area of triangle (see Fig. II.1).
[7]Discount rate = 5%.
[8]Discount rate = 10%.

Laboratory research yielded several innovations in cryogenic insulation over the next half century. In 1910, Smoluchowski demonstrated the superiority of a powdered insulation in the vacuum space over the vacuum alone, and by 1937 an evacuated powder insulation was widely adopted. In 1951, Peterson of the University of Lund (Sweden) invented an insulation composed of thin radiation shields (polished aluminum foil) spirally wound with glass fiber spacers. This multilayer insulation was many times more effective than the evacuated powders in reducing heat transfer through the walls of the storage vessel.

Cryogenic research had applications to various fields of government concern such as nuclear research, the Air Force, and the developing space program. It is, therefore, not surprising that Federal money helped support the programs from the very early 1940's. The cryogenics Laboratory at Ohio State University was established in 1942 as part of the Manhattan Project. Wright Patterson Air Force Base took over the support of their earlier work, and by the late 1940's there was significant support by NACA, NASA's predecessor. NACA support continued through the 1940's and early 1950's, resulting in a number of advances, including investigation of the properties of a large variety of insulators, development of a pump that could be used for transferring cryogenic liquids, and calculation of the thermodynamic properties of many cryogenic liquids.

By the time the space program began in earnest, it had become clear that the problem of storing hydrogen over a fairly prolonged period had to be solved, as the levels of heat loss and boiloff with con-

ventional insulations were too high for space program purposes. Liquid hydrogen had to be shipped over long distances and kept available for months rather than the week or so that was then possible. Also, the requirements for the insulation of the spacecraft's fuel tanks and for highly effective thermal shields for the spacecraft and space suits meant that much more effective and lighter weight products had to be developed. Throughout the 1950's, NASA actively encouraged the transfer of knowledge from the laboratories to the manufacturing process. Part of these efforts were centered at the National Bureau of Standards Cryogenic Laboratory, which was established in 1952 for cryogenic research.

Multilayer insulations were commercially available by 1958, at the inception of the space program, but they failed to meet NASA's needs in several respects. They were too fragile, variable in performance, and difficult to apply. NASA, therefore, addressed itself to the problems of advancing processes and techniques for fabricating and applying high-performance, high-reliability insulation systems. While some of this work was done in-house, significant contributions were also made by commercial contractors, including Boeing, Linde, NRC, and Goodyear Aerospace Corporation.

NASA's chief instrument in promoting technological advance was the performance contract. Contracts were let with specifications as to the function that would have to be performed by the resulting product. For example, McDonnell Douglas was approached to develop a separator which, with much simpler blueprints than had been available before, would give repeatable densities. No known separator fulfilled these requirements,

but McDonnell Douglas developed it with the existing technology, simultaneously fulfilling the contract and advancing the state of the art of liquefaction of gases.

If a problem did not lend itself to that approach, NASA employed a less structured approach. When such a problem arose, NASA would approach individuals or firms who seemed likely to be able to resolve it. For example, after the development of NRC-2, a thermalized shield of aluminized mylar, it was found that the insulation compressed when wrapped around corners, losing some of its effectiveness on the fold. Several firms experimented with alternative wrapping techniques, of which the most satisfactory was the use of a flocking machine like that used for Christmas decorations.

Two new forms of superinsulation specifically fulfilled the requirements of the space program. At the Buffalo Laboratory of Union Carbide, Dr. John Matsch had been concerned for some time with the development of an improved form of insulation because of the high rate of heat loss in the transportation of liquid oxygen, nitrogen, and argon. In addition, the requirements of the developing space program were recognized quite early by the Union Carbide management, and Matsch's effort was accelerated. By 1961, he had acquired patents on a new form of superinsulation composed of thin aluminum reflective shields with fiberglass spacers which has been estimated to be at least 20 times more effective than perlite. This insulation was particularly suitable to the prolonged storage of hydrogen and helium. In a parallel effort, the National Research Corporation secured the patent for NRC-2. With some subsequent improvements this product proved so effective and lightweight an insulation that it was used in both space suits and spacecraft.

The role of NASA in the development of cryogenic insulations is difficult to quantify, as it has been confined to defining the problem areas and seeking the facilities where solutions might best be found, with patents and recognition going to those firms who could fulfill NASA's requirements. Each problem solved provided a contribution to the advancing state of the art.

2. Speed-Up Due to NASA

The space program's need for cryopropellents, space chamber simulation, purging and pressurizing satellite sensors, and life support systems led NASA to invest in extensive R&D in cryogenic technology and particularly in superinsulation. Technological advance would undoubtedly have taken place in this field even in the absence of NASA's substantial investment. It is extremely likely, however, that the additional resources devoted to the research and development of cryogenic insulation caused an acceleration of the innovations. Thus, benefits that would have occurred as a result of industry R&D efforts probably began to appear earlier because of NASA's participation.

The major difficulty presented by this approach is the problem of determining how much NASA accelerated the innovations and, therefore, the stream of benefits. The problem is particularly difficult because of the nonspecific nature of many of NASA's contributions, which clearly advanced the "state of the art" even when they did not result in patentable inventions. In addition, NASA's great demand for cryogens represented a substantial part of the total demand in the late 1950's and early 1960's, particularly in the case of hydrogen and helium, and produced an additional incentive to industry to expand its own R&D efforts.

Research conducted by the Denver Research Institute indicates that in the field of cryogenics 23 percent of the major advances they studied would not have occurred without NASA's contributions, and 77 percent occurred earlier as a result of NASA's contributions.[7/] Discussions with non-NASA industry experts on cryogenic insulation in particular yielded the following five estimates of the speed-up due to NASA.

1 year

5-6 years

6 years

Indefinitely: developments would never have occurred (two estimates)

The calculations of NASA's share of the benefits were done using a minimum estimate of one year, a probable estimate of five years, and a maximum estimate of ten years. The ten year figure was chosen arbitrarily rather than using an infinite speed-up as the maximum.

3. Benefits Attributable to NASA

Table II.4 summarizes the benefits due to NASA, calculated for the years 1960 to 1983 and from 1960 into perpetuity. The projection method for estimating benefits through 1983 was described in Section B. Benefits were estimated for every year of the next decade and these figures were discounted and totaled. Since a decade is admittedly an arbitrary period over which to estimate future benefits, an alternative less conservative computation was made assuming that the stream of benefits attributable to NASA will continue indefinitely into the future.

Table II.4

1. Total Benefits ($ Million), 1960-1983:				
	Helium	Hydrogen[1]	Nitrogen	Total
a. 5% Discount Rate : PDV[2]	531	1535	61	2127
b. 10% Discount Rate : PDV	567	1542	64	2173

2. Benefits Attributable to NASA · 1960-1983			
	Number of Years Accelerated		
	1 Yr.	5 Yrs.	10 Yrs.
a. 5% Discount Rate PDV ($Million)	205	897	1504
b. 10% Discount Rate PDV ($Million)	263	1054	1663

3. Benefits Attributable to NASA:1960 to Perpetuity			
	Number of Years Accelerated		
	1 Yr.	5 Yrs.	10 Yrs.
a. 5% Discount Rate PDV ($Million)	285	1294	2303
b. 10% Discount Rate PDV ($Million)	289	1184	1926

[1] Excluding liquid hydrogen purchased by NASA. If NASA's purchases had been included, the figures for hydrogen would have increased to $1883 million (5%) and $2043 million (10%).

[2] PDV=Present Discounted Value expressed in 1974 dollars.

In order to determine that part of the benefits attributable to NASA, it was assumed that NASA accelerated the stream of benefits by a given time period, p . It was assumed that even in the absence of NASA's participation in the R&D process, advances in cryogenic insulation would eventually have been made, but p years later. In the case of liquid hydrogen and helium, NASA's participation resulted in cost reductions and, both directly and indirectly, demand increases: it simply was not feasible to ship these liquids in more than laboratory quantities before the development of multilayer insulation. Thus, NASA can be said to have contributed to the development of a new market and thereby to have caused the entire stream of benefits to be accelerated by p years. The difference was then calculated between the actual benefits in every year, $B(t)$, and the benefits in year $t-p$, $B(t-p)$ (assumed to be zero for the first p years). These differences $B(t) - B(t-p)$, were discounted and summed to obtain NASA's contribution through 1983. In the perpetuity case, the value of $B(t)-B(t-p)$ in 1983 was assumed to continue indefinitely into the future. On this assumption, the present value of post-1983 benefits was computed as of 1983; the resulting figure was then discounted back to 1974 and added to the sum of 1960-1983 benefits.

The case of liquid nitrogen was treated somewhat differently. Although NASA could be viewed as responsible for unit costs savings when multilayer insulation is used instead of perlite, the quantities of liquid nitrogen produced have apparently not been substantially altered by NASA's participation. Thus, the per unit benefit in year $t - p$ was

weighted by production in year t (rather than the production in year t - p), and the difference between this product and the actual benefits for each year was calculated, discounted, and summed. [8/]

D. Summary

The benefits of using reflective multilayer superinsulation instead of the next best substitute for liquid hydrogen, helium, and nitrogen transport tanks are considerable. The total benefits from 1960 to 1983 are estimated at $567 million for helium, $1542 million for hydrogen, and $64 million for nitrogen (given a discount rate of 10 percent). Boiloff savings account for over 98 percent of the total for hydrogen and helium; transportation savings account for about 97 percent of the total for nitrogen.

NASA's share of these benefits is substantial, even if estimated conservatively: if NASA can be said to have accelerated development of the new material by five years, and benefits are projected only through 1983, this share amounts to $897 million given a 5 percent discount rate. If a 10 percent discount rate is used, NASA's contribution is about $1054 million. If NASA can be said to have sped up development by ten years, these figures increase to $1504 million (5 percent) or $1663 million (10 percent).

These figures are biased downward for at least three reasons: one, whenever alternative reasonable assumptions were encountered, the decision was made to choose the one yielding the lowest benefits; two, only the boiloff savings during transportation, and not during production

and storage, were calculated; and three, only three of the many commercial applications of multilayer insulation were considered. Thus, the estimates of the benefits of this secondary application of NASA research and development would seem a conservative estimate of the "true" benefits.

FOOTNOTES - CHAPTER II

1. P. Glaser, Thermal Insulation Systems. NASA SP-5027. Cambridge: Arthur D. Little, 1967; phone conversation with CVI Corporation.

2. This assertion is based in part on a phone conversation with the Linde Division of Union Carbide.

3. This assumption is made to simplify the analysis. The results do not differ substantially if an upward sloping supply curve is assumed.

4. Differences in design costs occur because of the ease of applying perlite relative to multilayer materials; the nature of the latter necessitates consideration of such factors as optimum wrapping configurations.

5. Except where otherwise noted, the following assumptions were made in the calculations for all three cryogens. (Any outside sources for assumptions are indicated in parentheses. Complete references for all publications and a list of phone contacts are given in Appendix C.):

   i. All liquid hydrogen and helium and 10 percent of the liquid nitrogen is transported using multilayer insulation.

   ii. All liquid hydrogen, helium, and nitrogen is transported in 11,000 gallon tanks which can be loaded onto a truck and then, if necessary, transferred to a ship. These tanks are subject to standard external conditions of temperature and pressure. The 11,000 gallon capacity is a standard configuration (Gardner Cryogenics) which is used often, but by no means exclusively; a standard configuration was assumed in order to simplify the computations, especially since the exact distribution of tank sizes was not known.

   iii. All liquid hydrogen and nitrogen is transported by truck; liquid helium is transported by truck to domestic customers and by truck and ship for export. The average number of miles trucked is 400 for hydrogen and nitrogen, 800 for helium; the number of miles by ship is 3,500. The shipping mileage is based on the fact that most liquid helium is shipped from the East Coast to Western Europe. Trucking mileage is based on information on the time held [see assumption (v)] and is consistent with both data on average haul lengths (American Trucking Association, American Trucking Trends 1960-1973, and information on the location of cryogen producing plants.

iv. Multilayer insulation is 20 times more efficient than perlite, and the daily boiloff rates for one inch thick insulation are as follows (Air Products and Chemicals, Inc.; Gardner Cryogenics; Union Carbide Corporation):

	Helium	Hydrogen	Nitrogen
Perlite	34.20%	16.84%	5.00%
Multilayer	1.71%	.84%	.25%

The relative efficiency of multilayer versus perlite has been given as 20-50 times; however, the lower figure was used to give a more conservative estimate of the benefits. Helium tanks were assumed to have 3 inches of insulation (Gardner Cryogenics) and hydrogen tanks to have 1 inch of insulation (Air Products and Chemicals, Inc.), regardless of the type of insulation material. Nitrogen tanks were assumed to have 5 inches of perlite insulation or 1 inch of multilayer insulation, since these are the thicknesses actually used (Union Carbide Corporation). The differential boiloff while the cryogen is held in each case can be calculated as .886 (helium), .16 (hydrogen), and .0075 (nitrogen).

v. The average time in the transport tank for helium is 20 days (Gardner Cryogenics) and for hydrogen (Union Carbide Corporation; Air Products and Chemicals; Inc., U.S. Bureau of Mines) and nitrogen (Union Carbide Corporation) one day.

vi. The annual production of liquid hydrogen was calculated as .67 percent of total hydrogen production in 1972 and 1973 (U.S. Bureau of Census, Current Industrial Reports: Industrial Gases, and U.S. Bureau of Mines), but no such information was available for prior years. We did, however, have access to data on NASA's annual purchases of liquid hydrogen (NASA Washington Headquarters), which in mid- to late-1960's accounted for a substantial proportion of the total. An attempt was made to construct a series for the proportion liquified, α , by the following means:

(a) Assume that while NASA's purchases of liquid hydrogen were increasing (1960-1968), α was increasing.

(b) Assume that as NASA's purchases of liquid hydrogen declined (1968-1973), the slack in α was taken up by increased liquefaction for the private market. (This assumption is consistent with the pattern of increasing liquefaction in the helium market.)

(c) On the basis of (b), let a = .0067 for every year from 1968 on. Prior to 1968, let a be proportional to the percent of total hydrogen production purchased by NASA in liquified form, with the factor of proportionality computed on the basis of the 1968 figures.

The values of a computed in this manner are shown in column 2 of Table II.1. No further increase in a was assumed for the future, although this assumption is undoubtedly conservative and results in downward-biased estimates of post-1973 benefits. It is also likely that a downward bias occurs in the figures for the early 1960's as a result of the procedure outlined above. In addition, all liquid hydrogen computations were based on production less sales to NASA, since benefits based on sales to NASA could be construed as primary benefits.

vii. The annual production of liquid helium was computed by multiplying the total helium production (U.S. Bureau of Mines) by the proportion liquified (a). Figures for a were obtained for 1971-1974 from the U.S. Bureau of Mines. For 1965-1970 they were obtained by linear regression of a on exports (data on the nature of the relationship between a and helium exports: U.S. Bureau of Mines.) In the absence of data for years prior to 1965 (the first year helium exports were permitted by law), a was assumed constant at .05, a figure consistent with the 1965 figure and with general data on cryogenics from Stanford Research Institute, Chemical Economics Handbook. The values of α are shown in column 2 of Table II.2.

viii. Figures for annual production of liquid nitrogen were obtained from the U.S. Bureau of the Census, op. cit., and "Industrial Gases: Short of Some Goals But Still Growing," Cryogenics and Industrial Gases (Jan./Feb., 1971). It has been estimated that 10 percent of this amount is transported in multilayer insulated tanks and the remainder in perlite-insulated tanks (Union Carbide Corporation). This percentage was assumed to hold for every year from 1960 to 1983.

ix. The price of helium was \$15.50 per thousand cubic feet in 1960 and 1961, and \$35 per thousand cubic feet from 1962 to 1971 (Chopney, N.P., "What's Next for Helium?" Chemical Engineering (June 10, 1974), 40-42). These prices reflect the government's fixed price; the lower free market price reduced the average price at which helium was sold to \$21 in 1972 and \$30 in 1973 (Chopney, N.P., op. cit.). The prices of hydrogen are given by the U.S. Bureau of Mines and those of nitrogen by the U.S. Bureau of the Census, op. cit. Since nitrogen prices were not available for 1960-1963, it was assumed that the real price was constant from 1960 to 1964.

N.B. The prices of liquid hydrogen and helium were taken to be the average price at which the corresponding gas was sold. This assumption was made in the absence of actual price data for the liquids themselves, which are probably somewhat higher.

x. The costs per ton-mile for trucking were given by the American Trucking Association, op. cit. The corresponding cost for shipping was given by Transportation Consultants for 1973 and was assumed to have increased by the same proportion as trucking costs throughout the period.

xi. Each hydrogen and nitrogen truck was assumed to make 160 trips of 400 miles (800 miles round trip) each year, and the helium trucks to make 64 trips of 800 miles (1,600 miles round trip). The number of trucks needed for each cryogen can therefore be obtained by converting cubic feet of gas to the corresponding gallons of liquid and dividing by 11,000 gallons times 160 or 64. (The latter product, 11,000 time 160 or 64, represents the annual capacity of each truck.)

xii. The per year differential capital cost is $83 per tank. This figure was computed based on 20 year straight line depreciation and the cost of insulating tanks with both types of material (Linde Division of Union Carbide Corporation; Gardner Cryogenics). Inspection and maintenance costs were assumed to be the same, and the difference in capital costs was taken to be wholly reflected by this depreciation difference. The only exception is the initial design cost which appears slightly higher for multilayer ($45,000 for multilayer, $37,500 for perlite) (Union Carbide Corporation, CVI Corporation); this cost applies only to the first truck (since the design can, of course, be reused) and in the computations the difference was added to the differential depreciation figure for the first year.

xiii. The wholesale price index was used to convert current savings into 1974 dollars.

xiv. Risk-free rates of interest of both 5 percent and 10 percent were used to compute present value of benefits throughout the period of analysis.

xv. Hydrogen production estimates for 1974-1983 were obtained by using the results of a linear regression of 1960-1973 production against time to project future production. The proportion liquified, which has seemed to hold steady over the past few years, was held constant at the 1973 level.

xvi. Helium production, which has declined slightly since a peak in 1968, was assumed to remain at the 1973 level through 1983. The proportion liquified, which has steadily increased over the past ten years, was assumed to continue to increase as in the past to a maximum of 70 percent in 1983.

xvii. Liquid nitrogen production estimates for 1974-1983 were obtained by assuming that production will continue to increase at an annual rate of 8 percent, the average rate of growth between 1968 and 1973.

xviii. Prices in 1974 dollars will remain unchanged from what they were in 1973.

6. To illustrate the manner of computing the benefits in a given year, an example will be presented in terms of hydrogen for 1973. Net liquid hydrogen production represented about 150 million gallons (the equivalent of about 18 billion cubic feet of gas at standard temperature and pressure). Given a differential boil-off rate of .16, boil-off savings expressed in 1974 dollars amounted to $87 million. Given the assumptions about the number of trucks needed to transport this quantity of liquid hydrogen (see Footnote 5) and trucking costs, including both tonnage rates and the depreciation differential, transportation savings were an additional one million dollars. The total was then adjusted for the upward bias represented by the triangular area in Figure II. 1 and discounted by 5 percent and 10 percent interest rates to arrive at the 1974 present value of the benefits, equal to $85 million and $89 million, respectively.

7. Denver Research Institute, <u>Mission Oriented R&D and the Advancement of Technology</u>, a report to NASA, 1972.

8. Note that as a result of this procedure all of NASA's contribution for liquid nitrogen appeared in the first p years.

CHAPTER III:

GAS TURBINES IN THE PRODUCTION OF ELECTRIC POWER

CHAPTER III

GAS TURBINES IN THE PRODUCTION OF ELECTRIC POWER

A. Introduction

1. Brief Description of Technology

The basis of gas turbine technology in electric power production is the principle that the expansion of hot combustion gases can be employed to produce rotary motion in a fan. In gas turbines, stationary nozzles discharge a jet of hot gas, typically the product of combustion, against blades on the periphery of a turbine wheel. The jet of gas is deflected and slowed, while the blades receive an impulse force which is transmitted as a mechanical torque to a shaft. In the production of electric power, the rotational energy of this drive shaft is converted into electricity by means of a generator.

During the past decade, gas turbines have been increasingly used for the generation of electric power, though mainly as a source of peaking power and standby capacity. Two types of gas turbines are generally used: the aircraft derivative gas turbine, which is a high-performance, lightweight machine burning primarily high-grade fuels; and the industrial gas turbine, a larger, heavy-duty machine capable of using a wider variety of low-cost, low-grade fuels. Both types can be installed in a relatively short time compared to the five to seven years required for a conventional plant; this factor has been a major impetus for their growth since the Northeast power blackout in 1965.

2. Nature of Benefits Generated

Gas turbine technology has advanced considerably over time and has undoubtedly generated a wide variety of improvements in both flight and non-flight applications. However, the quantification of secondary benefits of NASA's gas turbine R&D concentrates on only one type -- fuel cost savings in producing electric power. The general assumptions and theoretical basis for using cost savings as a measure of economic benefits are discussed in Chapter I. This theory is merely recapitulated here in the context of gas turbine electric power production.

To begin, let ac^o be the fuel cost per unit of output of producing power with gas turbines of some reference, or base, year vintage. Let ac^i be the average fuel cost of power production for turbines of a later vintage. A fundamental assumption in this analysis is that later vintages incorporate the effects of advancing gas turbine technology and, ceteris paribus, exhibit improved fuel performance. In other words, ac^i will be less than ac^o. If this is so, then production with later vintages will generate fuel cost savings relative to production with the base-year vintage.

To illustrate, suppose in year t machines of vintage i produce q_t^i units of electrical power. Then the total fuel cost for turbines of vintage i would be $(ac^i)(q_t^i)$. On the other hand, if gas turbine technology had been arrested in the base year, the average cost of fuel would have remained at ac^o, and the cost of producing q_t^i with the earlier vintage turbines would have been $(ac^o)(q_t^i)$. The difference in these two costs would then be the vintage i fuel cost savings in year t. Notice that these cost savings are relative to what costs would have been if technology had not progressed from the base year level.

In any given year t, there will, of course, be a stock of gas turbines of different vintages and the total cost savings for the year must necessarily account for that fact. Specifically, if i is an index of turbine vintages since the base year, then the total fuel cost savings in year t due to the advancement of gas turbine technology from the base year would be

$$\sum_i (ac^o - ac^i)\ (q_t^i) \tag{III. 1}$$

Note that by equation (III. 1), the quantity produced by each vintage is weighted by the difference between its average fuel cost and the average fuel cost of the base year vintage. This accounts for the fact that, relative to the base year, technological progress generates greater fuel cost savings on output produced by newer vintage turbines and less on older vintages.

If ACF_t is the overall average fuel cost in year t, then

$$ACF_t = \frac{\sum_i (ac^i)\ (q_t^i)}{\sum_i q_t^i} \tag{III. 2}$$

Similarly, if technology had not advanced since the reference year, average fuel cost in year t, ACF_t^o, would have been

$$ACF_t^o = \frac{\sum_i (ac^o)\ (q_t^i)}{\sum_i q_t^i} \tag{III. 3}$$

With this notation, the total fuel cost savings given by equation (III. 1) can be written

$$(ACF_t^o - ACF_t)\ (Q_t) \qquad \text{(III. 4)}$$

where $Q_t = \sum_i q_t^i$.

Referring to Figure III. 1, let $ANFC_t$ denote the average cost of all factors other than gas turbine fuel in the production of electric power. Assume that it is unaffected by advancing gas turbine technology. Then if market price is at average total cost, the total fuel cost savings in equation (III. 4) approximates the increase in consumers' surplus due to electricity prices being at $P_t = ACF_t + ANFC_t$ rather than $P_t^o = ACF_t^o + ANFC_t$. That is, equation (III. 4) gives (approximately) the increase in economic benefits generated by advances in gas turbine technology which lower the price of electricity from P_t^o to P_t. The increase in consumers' surplus is represented by the shaded area in Figure III. 1.

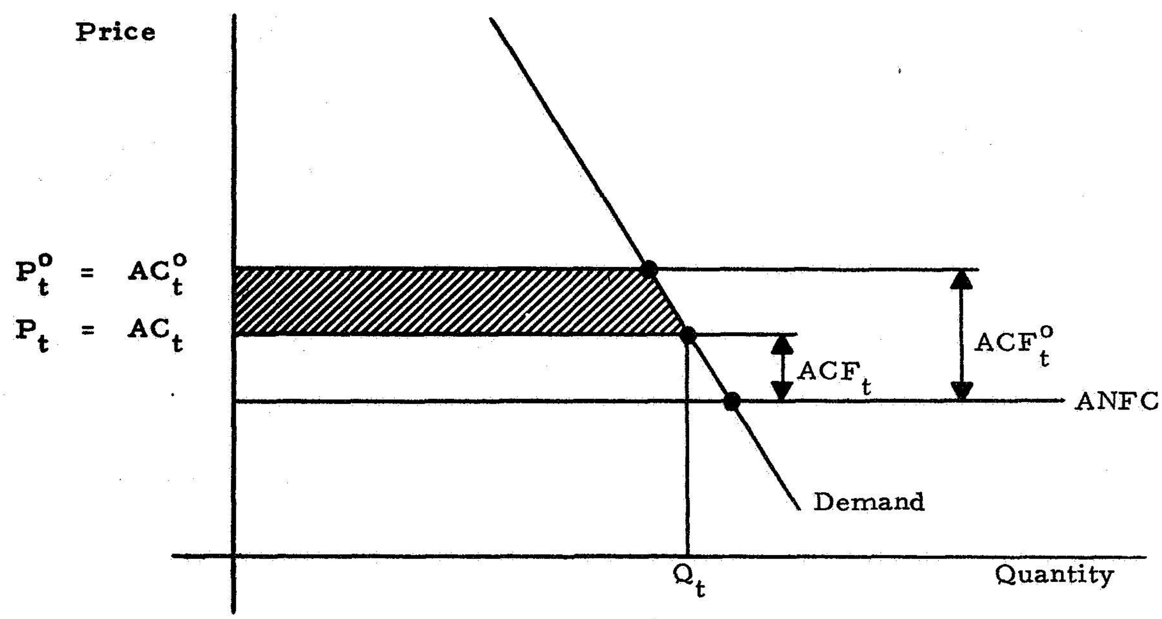


Figure III. 1

As suggested by Figure III. 1, in this chapter electricity is treated as a final good. Though it is both "final" and "intermediate" in the sense that some electricity is sold directly to households and some is sold to producers, the analysis can be simplified without radically altering the results by assuming all sales are to final consumers. This simplification is justifiable because, as indicated in Appendix A, the cost savings in the production of electricity used as an intermediate good, under reasonable conditions, approximate changes in consumers' surplus in markets for final goods and services produced with electricity.

Figure III. 1 also illustrates the case where electricity is produced under conditions of constant average cost -- an assumption about electricity production in this analysis. Though there is strong evidence suggesting declining average cost[1/], constant average cost is assumed in order to reduce the chance of overstating the benefits of advancing gas turbine technology. Consider Figure III. 2. If average cost is constant, and technology reduces it from AC^{o} to AC, then the increase in consumers' surplus is given by ACFG. If, on the other hand, average cost were declining and technology displaced the cost structure from $AC^{o'}$ to AC', the change in consumers' surplus would be ADEG -- a greater magnitude. In general, assuming constant average cost tends to be conservative.

However, under conditions of constant average cost, the estimate of benefits given by equation (III. 4) overstates the true change in consumers' surplus. Referring to Figure III. 2, the area ABC represents the error introduced by the cost savings approximation. Though the precise magnitude of the error depends on the elasticity of demand (the less elastic, the smaller

the overstatement) and the change in market price,[1] typically it is small relative to the change in consumers' surplus.

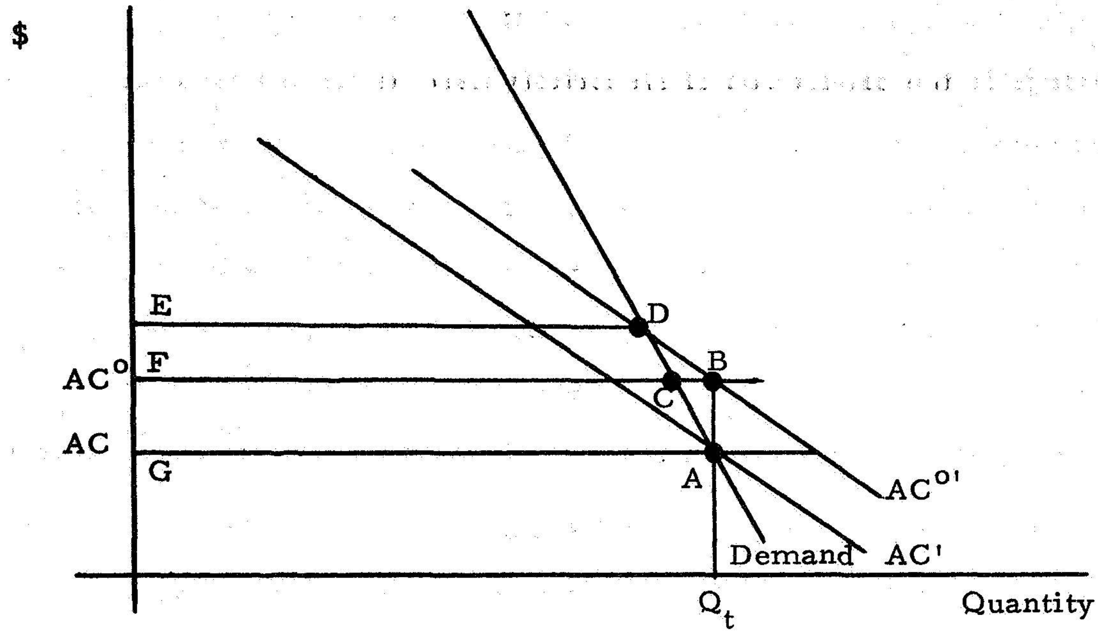


Figure III. 2

As noted in Chapter I, the actual percentage error is given by

$$\frac{1/2\eta k}{1-1/2\eta k} \times 100 \qquad \text{(III. 5)}$$

where η is the elasticity of demand and k the proportional change in price. Suppose, for the purpose of illustration, that the elasticity of electricity demand is 1.[2/] Further suppose that had gas turbine technology not advanced, the market price of electricity would be 1 percent higher because of additional

fuel cost in gas turbine power production. Using the above formula, the percentage error introduced by equation (III. 4) would be about 0.5 percent. This example is representative of the corrections made later in the chapter. In none of the estimates is the overstatement correction large; all are less than 1 percent. However, by assuming constant cost and making this correction, we reduce the chances that the estimated benefits exceed the true changes in consumers' surplus. [3/]

The sections below detail, in order, how: (1) the impact of advancing turbine technology on the average cost of fuel was estimated, (2) the total annual gas turbine fuel cost savings (economic benefits) were calculated and (3) part of the estimated benefits were apportioned to NASA.

Before proceeding, a final point requires clarification. Because applications of advancing gas turbine technology outside electric power production are excluded, the measure of benefits is obviously narrow. Moreover, this measure is narrow even within the field of electric power production. Improvements in gas turbine technology generate social benefits other than reduced fuel cost. For example, since gas turbines serve peak demand and augment standby capacity, they enhance the reliability of electricity service. They are relatively "clean" as well, and, thus, are desirable from an environmental point of view. Consequently, in addition to the conservative assumptions which guide the calculation of changes in consumers' surplus, the fact that these other benefits are

omitted from the evaluation is another reason for believing that the estimates understate the social benefits of advancing gas turbine technology in electric power production.

B. Measurement of Benefits

1. Methods Applied

The underlying rationale behind the cost function method employed in this case is discussed in Chapter I of this report. Essentially, the methods relate average cost to the level of technology so that cost savings due to advancing technology can be calculated. Once an estimated average cost function which explicitly incorporates a variable for the state of technology has been estimated, shifts in average cost, such as the movement from AC^o to AC in Figure III. 2, can be calculated.

In the present case, the link between average cost and technology is through gas turbine vintage. It was assumed that different vintages embody different levels of technical knowledge about the process of producing electricity with gas turbines, and that newer vintages embody higher levels of technical knowledge. Under these assumptions, turbine vintage can serve as a proxy for the level of technology and the relationship between average cost of fuel and turbine vintage can be estimated. This section describes how such a relationship was estimated using data on plant gas turbine power production in 1972.

Letting:

ACF = average cost of fuel for power produced with gas turbines,

Q = quantity of power produced with gas turbines,

C = installed gas turbine generating capacity,

T = turbine vintage,

the model of gas turbine fuel cost estimated is

$$ACF = f(Q, C, T) \quad . \qquad \text{(III. 6)}$$

Single equation regression analysis was employed to estimate various forms of Equation (III. 6). However, in each case the intent was to estimate, as precisely as possible, the coefficient of turbine vintage by controlling for the confounding effects of output and generating capacity on average fuel cost.

2. Data Sources

The data used in the regression analysis of equation (III. 6) come from two sources:

(a) Federal Power Commission, Gas Turbine Electric Plant Construction Cost and Annual Production Expenses, 1972.

(b) J. W. Sawyer and R. C. Farmer, "Gas Turbines in U.S. Electric Utilities", Part I and Part II, Gas Turbine International, January-February 1974 and March-April 1974.

The data in these two sources include information on approximately 300 gas turbine electric utility plants for 1972. They include figures on generating capacity, net generation, plant costs, fuel costs, number of turbo-generator units, and the year turbines were placed in service. In the regressions, however, only data for plants with single gas turbine units were used because the vintage of different turbines in plants with multiple units was obscured in the data. In all, there were 123 such plants. Furthermore,

the available data give only an imprecise measure of turbine vintage. Specifically, for turbines in the sample, the data indicate only the year of installation rather than the year each turbine was manufactured. Accordingly, this vintage variable is less than ideal. It is to be expected, however, that there would be a reasonably close relationship between year of installation and the extent, or level, of gas turbine technology, so that whatever lag exists between manufacture and installation is not crucial in the analysis. The important consideration is that turbines of different vintages (i.e., years of installation) will have embodied different levels of technology.

3. Results of Estimates

The results of the regressions are summarized in Table III. 1 . The method used to estimate the vintage coefficient was first to regress ACF on T and then to control progressively for other factors. In this way one could estimate T's marginal effect on ACF more accurately. Regression 1 in Table III. 1 is the simple regression of ACF on vintage. As expected, the vintage coefficient is negative and indicates that the average cost of fuel is reduced approximately .4 mills per KWH for every one year increase in installation year. The R^2 in regression 1 indicates that the overall explanatory power of the equation is low and that T's coefficient may be estimated more efficiently by adding controlling variables to the regression.

Perhaps the most obvious variable to introduce is power produced, for it will surely influence the average cost of fuel. To allow for both

Table III.1

Estimated Average Cost of Fuel Functions for Gas Turbines

Based on 1972 Data[1]

No.	Constant	Q	$\frac{1}{Q}$	C	$\frac{1}{C}$	C^2	$\frac{Q}{C}$	T	R^2	Description
1	15.027 (13.106)							-.413 (-2.706)	.0571	Naive Relationship
2	15.482 (15.520)	-.065 (-5.851)	.922 (2.710)					-.301 (-2.288)	.3250	Control for Output
3	15.238 (15.201)	-.069 (-6.094)	.950 (2.806)	.026 (1.612)				-.349 (-2.608)	.3396	Control for Turbine Size
4	17.751 (8.033)	-.071 (-5.872)	.948 (2.820)		-27.136 (-1.500)			-.415 (-2.521)	.3325	
5	15.381 (15.594)	-.068 (-6.125)	.912 (2.686)			.003 (2.010)		-.316 (-2.432)	.3473	
6	15.777 (15.439)	-.040 (-1.746)					-.676 (-1.266)	-.333 (-2.496)	.3341	Control for Utilization

[1] NOTES:

(a) Variables are:

ACF = average variable cost of fuel, mills per KWH (dependent variable)

Q = net generation 1972, millions of KWH

C = installed generating capacity, megawatts

T = machine installation year. 0 = 1961, 1 = 1962, . . .

(b) t - statistics appear in parentheses below estimated coefficients.

(c) All F ratios are significant at the 99% level.

(d) Sample size equals 123.

declining and rising ACF with output, both the quantity of power produced and its reciprocal were introduced in regression 2. Since the signs on the coefficients of Q and $\frac{1}{Q}$ are negative and positive, respectively, the average cost of fuel declines throughout the observed range of output.

The quantity coefficients are both significant and the equation's coefficient of determination is raised markedly. The vintage coefficient is reduced in magnitude but remains significantly negative. Controlling for output and turbine vintage in this fashion accounts for 33 percent of the observed variation in the average fuel cost of producing power with gas turbines.

Regressions 3, 4 and 5 introduce installed turbine capacity in various ways. All three indicate that, ceteris paribus, larger turbines have slightly higher average cost of fuel. However, in each case, the vintage coefficient remains significant and of the expected sign. Finally, in regression 6, a utilization variable, Q divided by capacity, is added. T's Coefficient again is negative and significant as in all the other versions of the estimated equation.

A striking feature of these results is that the coefficient of T is relatively stable across different specifications. Across all six specifications, T's coefficient is significantly negative and ranges from -.41 to -.30. This indicates that when the effects of quantity produced, installation capacity, and utilization are controlled, the average cost of fuel in gas turbine power production declines with turbine vintage. Relative to the average fuel cost in

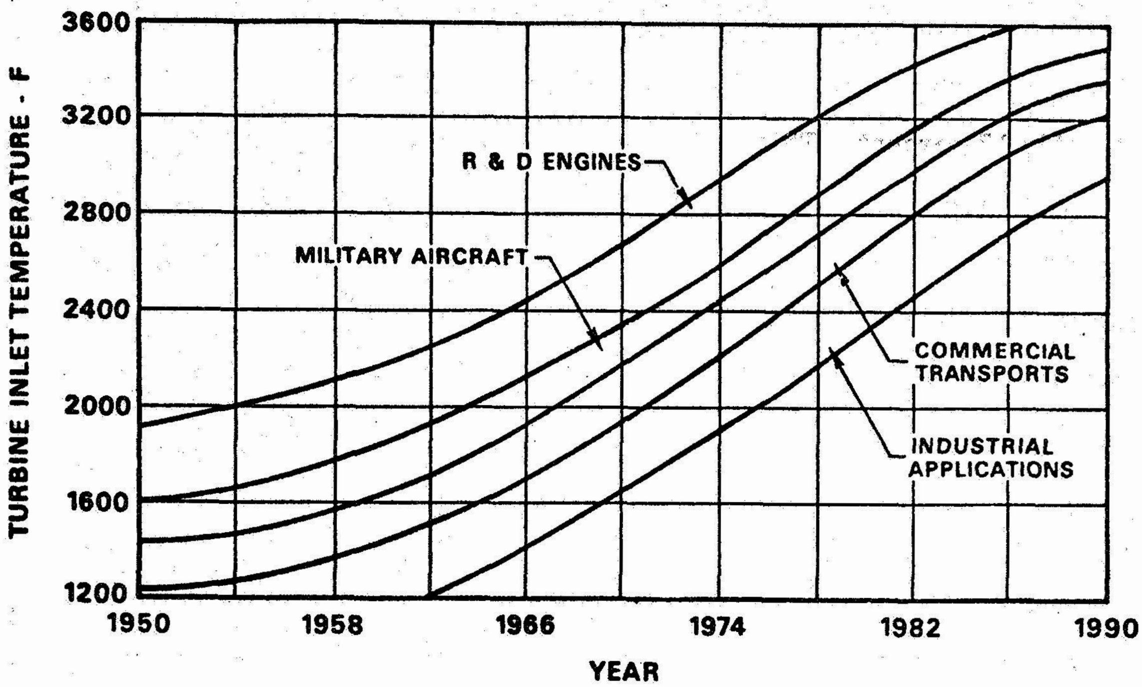
the sample, 12.1 mills per KWH, an average reduction due to turbine vintage of .3 mills represents approximately a 2.5 percent performance improvement per year. For the period 1965 to 1972, the total accumulated fuel performance improvement would be roughly 17 percent. This estimate is similar to other estimates of improved gas turbine efficiency. For example, Figures III. 3 and III. 4, from different sources, show improvements of approximately 25 percent in turbine inlet temperature and heat rate for the period 1965 to 1972. These two factors are crucial in determining the efficiency with which turbine fuels are consumed.

It was assumed that the estimated reduction in average fuel cost due to the decrease in turbine vintage can be attributed to advancing technology rather than to degradation of performance from machine usage. In addition to the comparability of the results with the above studies, discussions with various professionals within the field of gas turbine power generation indicate that the industry's typical regimen of normal periodic maintenance of gas turbines keeps turbines of a given vintage at or near installation efficiency. In fact, because some technological advances can be retrofitted in older vintages during routine overhauls, it is possible that the performance of older vintages could actually improve. One indication of the durability of gas turbines is that estimates of their service life in serving peak demands range from 20 to 30 years.

An attempt was made to provide partial empirical support for the assumption that there are not significant increases in the average cost of fuel due to "aging". Installations of a specific turbine model, United

Figure III. 3

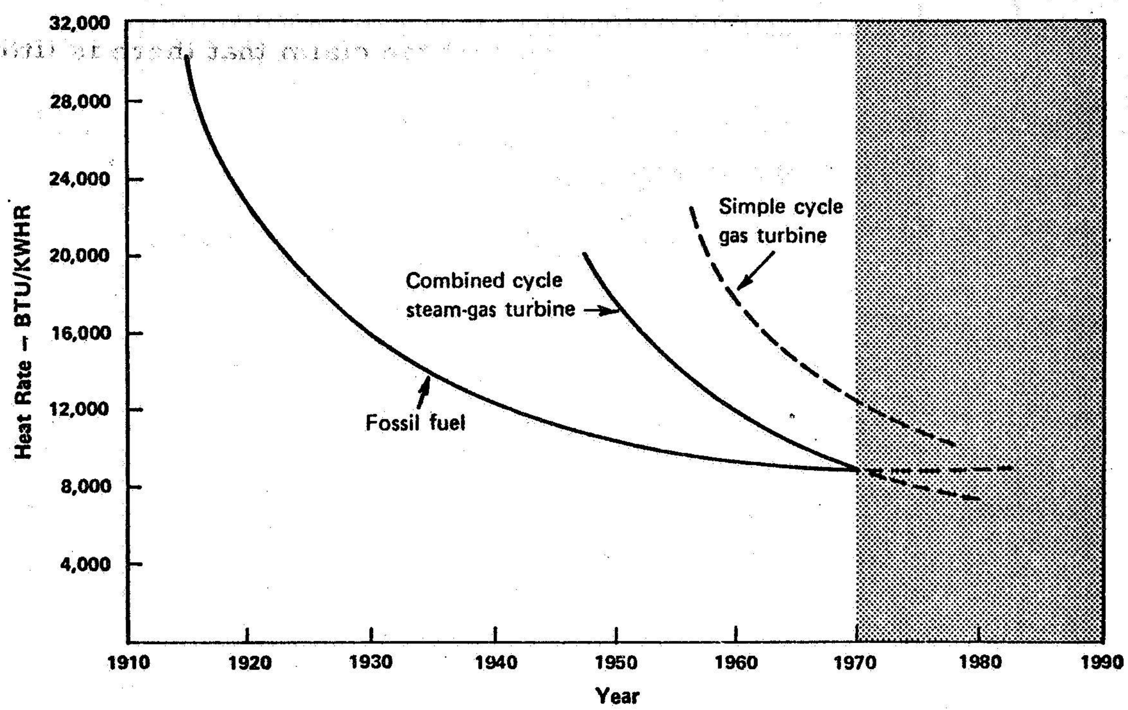
Estimated Turbine Inlet Temperature Progression



Source: Robson, F. L. and Giramonti, A. J., "The Effects of High-Temperature Materials on Combined-Cycle Performance", mimeo, United Aircraft Research Laboratories

Figure III. 4

Historic Heat Rate Improvement for Fossil Steam, Simple Cycle and Combined Cycle Gas Turbine Units



Source: Koeneman, J. K., "Gas Turbines -- The Coming Revolution in Industrial Power", Institutional Research Department, Oppenheimer & Co., New York, 1971.

Aircraft's (Pratt & Whitney) FT4A-8, in two consecutive years, 1968 and 1969, were identified. Assuming that the technological improvements for this specific model were small from one year to the next, then the 1972 average fuel costs for installations in these two years should shed light on how much one year's use increases average fuel cost.

Though the samples were small -- nine installations in 1968 and six in 1969 -- the results, rough as they are, support the claim that there is little or no significant performance deterioration with use over short periods. In fact, though the difference in average fuel cost for the two years was insignificant, 1969 installations had a slightly higher average fuel cost in 1972 than did 1968 installations.

To investigate further whether the vintage variable was trapping physical deterioration due to use, average heat rates obtained in 1972 generation -- the average number of BTU's used in producing a KWH of electricity -- were regressed on output, capacity and T. If T were measuring physical depreciation as well as the level of technology, then its estimated coefficient should tend to overstate the historical annual heat rate improvement illustrated in Figure III. 4. That is, if T measures, in part, physical depreciation, then the observed heat rates in 1972 on older turbines should be relatively high (poor) while those on new turbines should be relatively low. Under these circumstances, T's coefficient will be large and produce a relatively large estimated heat rate improvement.

Various regressions were run; however, the greatest (in absolute value) estimated coefficient on T is 370 BTU's per year. In other words, the largest estimated impact on heat rate indicates that each yearly

decrease in vintage reduced the observed heat rate in 1972 by 370 BTU's. This is approximately a 2.2 percent vintage-year improvement. For vintages 1965 to 1972, this would represent a total accumulated improvement of about 16 percent, which is considerably less than the historic heat rate improvement illustrated in Figure III.4. Consequently, it appears quite reasonable to conclude that T is not overstating technological improvements.

To summarize briefly, the cost function estimates indicate that, for each additional year, fuel cost is reduced, ceteris paribus, by .3 to .4 mills per KWH due to technological change embodied in turbines. In all the subsequent benefits calculations, however, the lowest estimated marginal impact of vintage on average fuel costs was used. Specifically, it was assumed that the annual reduction in average fuel cost for gas turbines due to vintage is .3 mills per KWH.

4. Calculation of Total Benefits

Calculation of the cost savings due to advances in gas turbine technology, given the estimated marginal impact due to machine vintage, is reasonably straightforward. For the most part, it involves a direct application of equation (III.1). There are, however, three basic issues which must be addressed. First, what base year should be used? Second, how far back in time should past benefits be calculated? Finally, what assumptions are to be made regarding future output growth?

Regarding the reference year for measuring technological growth, 1965 was chosen because the major growth in gas turbines in electric power seems to have started about then. This choice is quite conservative since substantial technological progress in turbines occurred prior to 1965. Certainly NASA's involvement in turbine technology (primarily aircraft type) predates 1965.

The answer to the second question was dictated by the available data. Total gas turbine power production is available for only the years 1969 to 1972. Therefore, past benefits were calculated for these years. Unfortunately, except for 1972, turbine output by vintage is not available. However, since the 1972 distribution of turbine vintage is available, preceding year vintage distributions could be easily generated by excluding the latest year installations. Consequently, for 1969 to 1972 the distribution of turbines by year of installation was obtained. To approximate the distribution of output by turbine vintage in years prior to 1972, it was assumed that the proportion of total turbine power produced by a particular vintage turbine is equal to the vintage's proportion of total turbine units [4/]. Thus, for each of the years 1969 to 1971, the distribution of power produced by turbines of differing vintages was estimated.

Once the distribution of output by turbine vintage was developed, equation (III. 1) was applied over the 1969 to 1972 period. Table III. 2 illustrates the basic calculations for the years 1972 and 1971. Similar calculations were performed for 1969 and 1970.

Table III.2

Cost Savings Calculations

(1972 Dollars)

	1972				1971				
Year of Installation	No. of Turbines[a]	Net Generation (Million KWH)[a]	Savings Factor (Mills/KWH)	Cost Savings ($000)	No. of Turbines	Proportion of Total Turbines	Estimated Net Generation (Million KWH)	Savings Factor (Mills/KWH)	Cost Savings ($000)
1965 & Before	39	1,020	0	0	39	.05	1,104	0	0
1966	32	536	.3	161	32	.04	883	.3	365
1967	77	2,109	.6	1,265	77	.10	2,207	.6	1,324
1968	123	2,545	.9	2,291	123	.16	3,531	.9	3,178
1969	138	2,993	1.2	3,592	138	.18	3,973	1.2	4,768
1970	172	6,118	1.5	9,177	172	.22	4,856	1.5	7,284
1971	203	7,672	1.8	13,810	203	.26	5,738	1.8	10,328
1972	111	3,931	2.1	8,255	—	—	—	—	—
Totals	895	26,924		$38,551	784		22,071[b]		$27,147

a. From Sawyer and Farmer, op. cit.

b. From FPC, op. cit.

To obtain cost savings for subsequent years, it was necessary to make assumptions about the future growth in turbine output. Again very conservative assumptions were made. From 1969 to 1972, turbine output grew at approximately 50 percent per year. In 1969, 8,127 million KWH were generated, whereas in 1972 the total was approximately 26,974 million KWH. However, it was assumed that post-1972 output grew at only 10 percent per year [5/]. It was further assumed that technology remains at the 1972 level and, consequently, that all increased output is produced with turbines embodying 1972 level technology. In other words, the post-1972 yearly increase in output is accounted for by 1972 vintage additions to the turbine population.

Using the procedure illustrated in Table III.2, total benefits were calculated for each post-1972 year. Note, however, that these benefits are all in 1972 dollars and have not been adjusted for the small overstatement error indicated earlier by equation (III.5). When one makes this correction, the 1972 benefits (in 1972 dollars) are $38.5 million. [6/]

The corrected figures were converted to 1974 dollars using the wholesale price index. [7/] The time stream (undiscounted) of estimated benefits is illustrated in Table III.3. Naturally, these benefits are not wholly attributable to NASA's role in gas turbine development. In the following section, a part of these benefits is apportioned to NASA.

Table III. 3

Benefits From Advancing Gas Turbine Technology

(Millions of 1974 Dollars)

Year	Benefits
1969	8.6
1970	20.8
1971	35.1
1972	50.1
1973	59.0
1974	67.1
1975	75.8
1976	85.7
1977	96.3
1978	108.2
1979	121.0
1980	135.3
1981	150.9
1982	168.1

C. Assignment of Benefits to NASA

1. Chronology of Developments

One of the earliest turbine-type applications was the smokejack, a device designed to operate with the aid of hot gases rising from a fireplace. The smokejack is believed to have first been sketched by Leonardo da Vinci, but it was described more fully by an English clergyman in 1648. The first patent for a gas turbine operating on a cycle resembling modern systems was issued in England in 1791. Though the machine could not have operated successfully, it incorporated most of the essential elements found in today's gas turbines. The first operational gas turbines originated in a number of European countries around the turn of the 20th century. These early turbines suffered from very poor thermal performance, primarily the result of poor compressor performance and limitations on the turbine inlet temperatures due to the lack of high quality materials.

Turbine driven compressors appeared in the 1920's. However, a perhaps more significant step in turbine development occurred in the late 1930's with Great Britain's jet engine development program which resulted in military jet aircraft used during World War II. In 1941, similar efforts to develop jet aircraft engines were initiated in the United States. Specifically, NASA's (at the time known as NACA) Lewis Research Center (LeRC) became actively involved in research and development in the field of gas turbines. Since the early 1940's Lewis Research Center

has made fundamental contributions to gas turbine technology. The list of Lewis' achievements in turbine technology is quite extensive. Much of the early research on turbine blade and stator cooling methods which permit higher turbine inlet temperatures and, therefore, higher turbine efficiencies, was conducted at Lewis. Blading, fans and compressors have been investigated for many years at Lewis and numerous LeRC procedures for analyzing flow dynamics have been developed.

Bearings research at LeRC, particularly for high temperature gas turbine applications, has produced test data and analyses on hundreds of rolling and fluid film bearings, as well as thousands of bearings components. Over the years at LeRC analyses of seal materials, seal designs, lubricants, high speed shafting and high speed gearing have produced basic understanding in these subjects, in addition to solutions of practical problems.

Lewis has established important relationships between test results and the performance of materials in engineering applications. A widely used method for analyzing stresses in turbine disks was developed at LeRC. Presently, NASA is studying problems encountered at compressor ratios between 30 and 40, with turbine inlet temperatures above 3000°F. Noise reduction and turbine control are two other areas of current research at LeRC.

2. Speed-Up Due to NASA

NASA's past involvement in the development of gas turbine technology has, no doubt, been rather extensive. In a previously referred

to study, the Denver Research Institute concluded that for "developments related to gas turbine aircraft engines and further, the use of such engines in non-aircraft applications", 92 percent of the advancements occurred earlier than they otherwise would have, due to NASA's contributions, and 8 percent occurred due to the parallel contributions of NASA and others. 8/

The estimates of speed-up used were based on discussions with six experts in gas turbine technology. All were outside the NASA community; they included people from industry and academia. Each was asked to give a minimum and a probable estimate of the extent to which NASA sped up gas turbine technology. The six estimates acquired were:

1/2	Year	
1/2 - 1	Year	(two estimates)
1/2 - 2	Years	
1 - 3	Years	
1 - 4	Years	

A speed-up of six months was taken as a minimum, one year as a probable, and four years as a maximum.

3. Benefits Attributable to NASA

Essentially, the benefits attributable to NASA are those that arise from causing fuel cost saving to accrue earlier rather than later. Consider Table III.4 , which illustrates how the calculation was performed for the 1972 benefits due to NASA's participation in gas turbine

Table III. 4

Calculation of 1972 Benefits Attributable to NASA:

(Thousands of 1972 Dollars)

Year of Installation	No. of Turbines	Net Generation (Million KWH)	Savings Factor (Mills/ KWH)	Cost Savings ($000)	Savings Factor (Mills/ KWH)	Cost Savings ($000)
1965 & Before	39	1,020	.0	0	.0	0
1966	32	536	.3	161	.0	0
1967	77	2,109	.6	1,265	.3	632
1968	123	2,545	.9	2.291	.6	1,527
1969	138	2,993	1.2	3,592	.9	2,694
1970	172	6,118	1.5	9,177	1.2	7,342
1971	203	7,672	1.8	13,810	1.5	11,508
1972	111	3,931	2.1	8,255	1.8	7,076
Totals	895	26,924		38,551		30,779

Benefits Attributable to NASA $38,551 - $30,779 = $7,772

technology. The first step was to determine the fuel cost savings which would have arisen had NASA not existed. The "without NASA" columns in Table III. 3 depict a one-year delay of cost savings due to the absence of NASA's contributions. Thus, had NASA not been present, the technological advance related to fuel cost simply would have occurred a year later, and the "without NASA" saving factors are shifted back one year. On this basis, the cost savings that would have occurred in 1972 without NASA amounts to $30.8 million.

The previously calculated 1972 benefits (uncorrected) were $38.6. The difference between these benefits and those that would have occurred in NASA's absence is the 1972 benefits attributable to NASA. In this example, they are $7.8 million (in 1972 dollars). Similar calculations were performed for each year from 1969 to 1982.

The estimated yearly benefits due to a one-year NASA speed up are given in Table III. 5. The post-1972 benefits remain at the 1972 level, due to the relatively conservative assumption regarding gas turbine technological progress. Recall that no post-1972 advancement in gas turbine technology was assumed. Consequently, technology in NASA's absence catches up in 1973 and, thus, the increase in output in 1973 (and subsequent years) is produced with 1972 vintage turbines under either case. As a result, of course, the post-1972 benefits attributable to NASA are left unchanged.

Table III. 6 summarizes, in present value terms, the estimated benefits due to NASA. Two intervals are shown· 1969-1972, and 1969-1982. The first is the time period for which data on gas turbines

Table III. 5

Annual Benefits Attributable to NASA: One-Year Speed-Up (Millions of 1974 Dollars)

Year	Annual Benefits Attributable to NASA
1969	2.9
1970	5.7
1971	8.3
1972	10.1
1973	10.1
1974	10.1
1975	10.1
1976	10.1
1977	10.1
1978	10.1
1979	10.1
1980	10.1
1981	10.1
1982	10.1

Table III. 6

Present Value of NASA Benefits
Gas Turbines in Electric Power Production
(Millions, 1974 Dollars)

Benefits Interval	NASA Speed-Up					
	Six Months		One Year		Four Years	
	5% Discount	10% Discount	5% Discount	10% Discount	5% Discount	10% Discount
1969-1972	15.3	18.1	30.6	36.2	108.7	125.4
1969-1982	58.3	55.6	116.5	111.2	516.7	479.1

are available and includes estimates of benefits which have already been realized. The second includes estimates of benefits which will be realized in future years. 9/

D. Summary

This case study addresses the problem of estimating the economic benefits in the field of electric power production of NASA's impact on gas turbine technology, a complicated task requiring many assumptions, approximations, and judgments. In the course of the analysis an effort was made to be conservative; to the extent that this effort was successful, the estimates have a downward bias. It would be imprudent, however, to interpret the results presented here as more than a first order approximation. They should be taken as reasonable, although rough, estimates.

The measure of economic benefits -- fuel cost savings in gas turbine production of electric power -- is obviously narrow. However, fuel costs are a large portion of the cost of producing electric power; average fuel costs are approximately 83 percent of the total average cost of producing electric power with gas turbines. 10/ Consequently, the benefits of fuel savings can be quite significant.

The methodology employed involves estimating the impact of advancing turbine technology by explicitly introducing a technology proxy -- turbine vintage -- into an estimated cost function. Based on 1972 data, the reduction due to advancing technology in the average cost of fuel was estimated to be in the range of .3 to .4 mills per KWH per year. In all subsequent estimates of benefits, the lower bound of .3 mills was used.

The year 1965 was used as a reference point. In particular, for the years 1969 (the earliest year for which there were data) to 1982, the fuel costs of producing that year's gas turbine-electric power were calculated, assuming the power had been produced with 1965 vintage turbines. The difference between the fuel cost with 1965 vintage turbines and the actual costs for a given year is the fuel cost savings associated with advancing technology for that year.

For the interval 1969 to 1972, benefits were calculated using actual data on gas turbine power production. For the years 1973 to 1982, benefits were calculated assuming a 10 percent growth rate in output and no post-1972 technological advance. Using a 10 percent rate of discount, the 1974 present value of these benefits over the entire period is $852 million (1974 dollars). With a 5 percent rate of discount, the present value is $977 million.

A part of these benefits was apportioned to NASA by assuming that the effect of NASA's presence was to advance the time stream of benefits. Assuming, for example, that NASA sped up the state of turbine technology by six months, the benefits attributable to NASA were $55.6 million (1974 dollars, 10 percent discount rate) for the period 1969 to 1982. Assuming a one-year advance, the benefits were $111.2 million over the period.

In conclusion, it should be noted that the fuel cost savings in gas turbine electric power production are only a portion of the total benefits of NASA's advances in turbine technology. Those that have accrued in aviation -- faster, safer flights as well as fuel savings -- may be substantial in comparison.

FOOTNOTES - CHAPTER III

1. See Nerlove, Marc, "Returns to Scale in Electricity Supply," Reprinted in Readings in Economic Statistics and Econometrics, edited by Arnold Zellner, Boston, 1968.

2. Most empirical studies indicate inelastic demand for electricity. See, Cargill, Thomas and Meyer, Robert, "Estimating the Demand for Electricity by Time of Day," Applied Economics, Vol. 3, 1971.

3. Recall that if there is declining average cost -- the usual assumption concerning regulated "natural monopolies" such as electric power producers -- there will be consumers' surplus CDEF (see Figure III. 2) unaccounted for by Equation (III. 4). CDEF offsets the overstatement ABC. However, even in the declining cost case, unless the overstatement error ABC is eliminated, it is in principle possible for Equation (III. 4) to overstate the true change in consumers' surplus.

4. This is a conservative assumption with respect to the benefit calculation, for later vintages produce slightly more than their proportional share.

5. See Koeneman, J. K., "Industry Report: Gas Turbines - The Coming Revolution in Industrial Power", Industrial Research Department, Oppenheimer and Co., New York, 1971, for a more detailed forecast. Koeneman argues that 1970 to 1980 annual growth will be in the neighborhood of 13 percent.

6. Two values are required to make the correction: the percentage change in market price and the elasticity of market demand. In the calculations it was conservatively assumed that the elasticity of demand is unitary. (Empirical estimates presented, for example, by Cargill and Meyer, op. cit., range from .15 to .58). Furthermore, the proportional change in price was taken to be equal to the proportional change in the average total cost of electricity. The proportional change in average total cost of electricity is given by

$$k = \left[\frac{t}{t + r(1-t)}\right] f$$

where t = the proportion of electricity output produced by gas turbines;

r = the ratio of the average total cost of production with other modes (steam, nuclear) to gas turbine average total cost;

f = the proportional increase in gas turbine average fuel cost.

To illustrate how the error corrections were made, consider the 1972 calculation. First, it was assumed that $r = .5$; i.e., gas turbines have an average cost twice that of other modes. This would approximate the ratio of average cost if each mode were operated at a 75 percent capacity factor. Typically, gas turbines are operated at capacity factors between 10 and 15 percent where r would be substantially greater than 1. (See Shortt, J. H., "Power Generation Economics," Gas Turbine International, January-February, 1974.) Referring now to Table III.2, since the total fuel cost savings from technological advance from 1965 is $38.6 million, the average fuel cost savings per KWH produced would be 1.43 mills. As the 1972 average fuel cost was 11 mills per KWH (see Federal Power Commission, Gas Turbine Electric Plant Construction Cost and Annual Production Expenses, 1972), had technology not advanced, average fuel cost would have been 13 percent higher. Noting that gas turbines accounted for approximately 2 percent of the total 1972 output, it follows from the above equation that $k = .005$. With $\eta = 1$, the overstatement is then .3 percent. The largest percentage overstatement, .4 percent, occurred in 1982.

7. In 1972 the WPI stood at 119 while in 1974 it was 155 (U.S. Bureau of Labor Statistics, Wholesale Prices and Price Indexes). The implied conversion factor is therefore 1.3.

8. Denver Research Institute, Mission-Oriented R&D and the Advancement of Technology, a report to NASA, 1972, Vol. 1, p. 22.

9. The benefits of NASA's advancing gas turbine technology, as reported in Table III.4, were based (essentially) on the following assumptions:

   (i) Post-1972 total net generation grows at 10 percent per year until 1982.

   (ii) Gas turbine technological advance stops in 1972 and additional output is produced with 1972 vintage turbines.

   (iii) Post-1965 installations remain operative through the period 1966 to 1982.

These are by no means the only "correct" assumptions, nor are they the only plausible set. Our analysis explored several alternative assumptions. In particular, consider (ii) and (iii) above. The table below summarizes the results, for a one-year and four-year speed-up, of replacing (ii) and (iii) with

   (ii') Post-1972 fuel cost savings occur at .1 mills/KWH per vintage year until 1982.

   (iii') Gas turbines collapse 10 years after installation and are replaced by the latest available vintage.

Present Value of NASA Benefits

1969 - 1982

(Millions of 1974 dollars)

Assumptions	One Year Speed Up		Four Year Speed Up	
	5% Discount	10% Discount	5% Discount	10% Discount
i, ii, iii	116	111	478	447
i, ii', iii'	129	121	517	479

Comparing row 1 and row 2, for example, indicates that the results are not drastically altered by the change is assumptions. Benefits attributable to NASA increase by approximately 10 percent under assumptions (i), (ii'), and (iii').

It should be further noted that because of the complex nature of the assumptions involved (for example, with regard to depreciation) in a projection into perpetuity, such a projection was not made in this case study.

16. From Federal Power Commission, op. cit.

CHAPTER IV:

INTEGRATED CIRCUITS

CHAPTER IV

INTEGRATED CIRCUITS

A. Introduction

1. Brief Description of Technology

Until 1960, conventional circuitry was built by the assembly of individually-encapsulated circuit components such as transistors, resistors, capacitors, and diodes. At that time, methods were developed to combine and interconnect these circuit elements and to associate them inseparably with a continuous base material, known as a substrate, to form an integrated circuit.[1/]

Integrated circuit technology provides significant advantages over conventional circuit technology. It offers smaller size, lower power consumption, increased speed of operation, improved reliability, and, most importantly, reduced cost per electronic function. Since most of the required interconnections are made within the integrated circuits, system design and realization are simplified. Thus, it is not surprising that integrated circuits have been the fastest growing segment of electronic component technology during the past fifteen years.

There are three basic types of integrated circuits: monolithic integrated circuits, multichip integrated circuits, and film integrated circuits.[2/] Monolithic integrated circuits consist of circuit elements

that are prepared within and upon the semiconductor[3/] substrate, at least one element being within the substrate. In most instances, the semiconductor substrate consists of a thin wafer which has been cut from a single crystal of silicon.

Multichip integrated circuits consist of two or more chips of semiconductor material assembled on a substrate. Although the substrate provides interconnection and isolation between the chips, the circuit elements are contained on the chips alone. A particular chip may contain a single element or may be a monolithic integrated circuit.

The circuit elements of film integrated circuits are formed of films deposited on an isolating substrate. Usually these elements consist of passive components, such as resistors, which impede the flow of electric current, and capacitors, which store electric charge. Depending on the technique employed for depositing the films on the substrates, these circuits are referred to as thin-film or thick-film.

2. Nature of Benefits Generated

While reductions in weight and size and improvements in reliability are important attributes of integrated circuits, by far the most important advantage that integrated circuits offer is a dramatic reduction

in cost per electronic function. This cost reduction results in part from large-scale integration, or the ability to combine hundreds -- even thousands -- of integrated circuits on a single substrate. In addition, in the past fifteen years, there have been continued improvements in integrated circuit production equipment, measuring techniques, and batch fabrication. These have resulted in improved process control and rapid increases in production yield, and, thus, in lower production costs.

Once it became economical to produce integrated circuits, the advantages of size, weight, and reliability combined to make widespread military, aerospace, and commercial applications possible. In particular, there was much interest and work on Metal-Oxide Semiconductor (MOS) structures and processes during the 1960's, as they require fewer fabrication steps than bipolar units (an earlier version), and, thus, promised very low production costs.

One example of the benefits associated with the development of complex MOS circuits is provided by desk calculators. Before complex MOS circuits were available, most desk calculators were assembled from electromechanical components or bipolar integrated circuits, and cost between $500 and $1,000. In the mid-1960's, a typical electronic calculator contained from 90 to 150 bipolar integrated circuits. By 1969, MOS technology had developed to the point that four MOS integrated circuits could perform the same functions. The small pocket calculator came on the market in 1972, priced between $50 and $200 and made possible by the reduction of the necessary circuitry to a single MOS device. Today, the cheapest calculators retail for less than $20, and total sales have risen from 5 million units in 1972 to an estimated 25 million in 1974.[4/] Virtually all small calculators on the market today are designed around MOS circuits.[5/]

B. Measurement of Benefits

1. Methods Applied

The use of semiconductor materials to realize electronic functions has revolutionized many fields of electronics. Development has proceeded from discrete devices to integrated circuits in which transistors and other elements can be functionally contained on a small chip. While it is true that discrete devices and integrated circuits can be considered rough substitutes, the low cost, miniaturization, and reliability made possible by the latter represent a significant advance both technologically and in new applications for which the use of discrete devices would not be feasible. Therefore, it seems justifiable to consider integrated circuits as a new product.

Given the treatment of integrated circuits as a new product, direct estimation of the demand curve seems fruitful in that it allows for the quantification of benefits in terms of the consumers' surplus (CS) area under the demand curve at each point in time. As is agrued in Appendix A, the consumers' surplus area measured on the demand curve for an intermediate good -- such as integrated circuits -- is equal to or a good approximation of economic benefits as defined in Chapter I.

As a naive first model, it might be postulated that the demand for integrated circuits is a function of its own price, the prices of substitute and complementary goods, and the demand for final goods using integrated circuits. The supply of integrated circuits, on the other hand, is a function of their price as well as the prices of factors of production and materials. Symbolically, this model consists

of two equations with an identity which ensures that the quantity demanded equals the quantity supplied in equilibrium. (An implicit assumption is that the industry can be characterized as competitive.)

Demand Equation: $Q^d_{ic} = f(P_{ic}, P_c, P_s, P_I, E)$

Supply Equation: $Q^s_{ic} = f(P_{ic}, P_F, P_m, P_I)$

Identity: $Q^d_{ic} = Q^s_{ic}$

Where:

Q^d_{ic} = quantity of integrated circuits demanded.

Q^s_{ic} = quantity of integrated circuits supplied.

P_{ic} = price of integrated circuits.

P_c = price of complements.

P_s = price of substitutes.

P_I = general price index.

P_F = price of factors of production.

P_m = price of materials.

E = expenditures on final goods using integrated circuits.

From one time period to the next, both curves are expected to have shifted. The demand curve shifts in time in response to changes in expenditures for the final products, and the supply curve shifts because of changes in the prices of factors and materials and fabrication technology. These movements are accounted for empirically by the inclusion of the remaining shift variables.

The estimating equations may take the following form:

$$Q_{ic} = \alpha_0 + \alpha_1 \frac{P_{ic}}{P_I} + \alpha_2 \frac{P_s}{P_I} + \alpha_3 \frac{E}{P_I} + U_d \qquad \text{(IV. 1)}$$

$$\frac{P_{ic}}{P_I} = \beta_0 + \beta_1 Q_{ic} + \beta_2 \frac{P_F}{P_I} + \beta_3 \frac{P_m}{P_I} + U_s \qquad \text{(IV. 2)}$$

Once the parameters of (IV. 1) are estimated, the calculation of benefits is relatively straightforward. At any point in time, the values of the shift variables will provide an estimate of the intercept of the curve. With knowledge of the intercept, the price, and the quantity demanded, the relevant consumers' surplus can be calculated for each of the sample years. The analysis can be extended to extrapolate future values of CS under alternative assumptions regarding the future values of the shift variables, assuming that α_1 in (IV. 1) remains constant.

2. Data Sources

The variables which are used to measure the benefits directly in Section 3 below are

Q_{ic}	=	Quantity of integrated circuits (millions of units).
P_{ic}	=	Price of integrated circuits (dollars).
E	=	Expenditures on electronic products (millions of dollars).
ACL	=	Average cost of labor used to produce integrated circuits.

ACM = Average cost of materials used to produce integrated circuits.

P_W = Wholesale price index for electronic machinery and equipment.

The sample period covers the years from 1963 to 1972, the earliest and most recent for which data are available. The yearly series on Q_{ic}, P_{ic}, and E were obtained from the Electronic Market Databook 1973, published by the Electronic Industries Association. ACM and ACL were constructed by first multiplying the total cost of materials and the wage bill, respectively, in SIC 3674 (semiconductors and related devices) by the ratio of PQ_{ic} to the value of shipments in that SIC and then dividing each by Q_{ic}. The total cost of materials, the wage bill, and value of shipments in SIC 3674 were obtained from the 1972 Census of Manufacturers Industry Series, U.S. Department of Commerce. In order to express money variables in terms of constant year dollars, P_{ic}, E, ACL, and ACM were deflated by P_W, where P_W is the Wholesale Price Index for Electronic Machinery and Equipment acquired from the U.S. Department of Labor, Bureau of Labor Statistics.

3. Results of Estimation

The first step in calculating benefits attributable to NASA was to estimate the demand function for integrated circuits using a Two Stage Least Squares procedure. It was found that the best fit was provided by a model expressed in a multiplicative form, which is linear in logarithms, as described by equation (IV.3a) and (IV.3b), below.[6] A demand

function should, theoretically, contain the prices of close complements and substitutes. However, the research conducted for this case study indicates that the integrated circuit is such a revolutionary product that it has no close substitutes and complements. They were omitted from (IV. 3a).

$$\text{Demand:} \quad Q_{ic} = \alpha' P_{ic}^{\beta'} E^{\gamma'} e^{u_1} \qquad \text{(IV. 3a)}$$

$$\text{Supply:} \quad P_{ic} = \delta(ACM)^{\epsilon} (ACL)^{\eta} (Q_{ic})^{\xi} e^{u_2} \qquad \text{(IV. 3b)}$$

where $\alpha', \gamma', \delta, \epsilon, \eta, \xi > 0$; $\beta' < 0$; u_1, u_2 = Disturbance terms.

Estimation of the simultaneous equation model represented by (IV. 3a) and (IV. 3b) indicated that ξ, the coefficient of Q_{ic} in the supply equation, was not significantly different from zero at the 95 percent confidence level. This result is not surprising in light of a previously reported finding that there do not seem to be significant economies of scale in the production of semiconductor products.[7/] This information was used to form a prior restriction that the coefficient of Q_{ic} in the supply equation, ξ, equals 0. This implies a horizontal average cost curve and permits the model to be treated as a recursive system. If it could be demonstrated that $Cov(u_1, u_2) = 0$, (IV. 3a) and (IV. 3b) could then be estimated directly using Ordinary Least Squares. However, since there is no prior evidence that this assumption would hold, greater precision in the point estimation is gained by estimating (IV. 3b) lirectly, and using the fitted values of P_{IC} as a regressor in the demand function (IV. 3a). This procedure yielded the following demand curve (t-statistics in parentheses): [8/]

$$\hat{\ln Q} = -15.5373 - 1.6055 \hat{\ln P} + 2.1446 \ln E \qquad (IV.4)$$

$$(-1.9573)(-12.8167) \qquad (2.7631)$$

$$\bar{R}^2 = .996$$

$$F_{2,7} = 1005.33$$

$$D.W. = 1.98$$

Note that the overall fit is quite good, the coefficients are highly significant and serial correlation is not indicated.

4. Calculation of Benefits

In order to calculate benefits in the form of consumers' surplus, the estimated demand curve was employed, after it was solved for P in terms of Q and E in the form:

$$P = \alpha Q^{\beta} E^{\gamma} . \qquad (IV.5)$$

The estimated equation (IV.4) can be expressed in multiplicative form as

$$Q = (.1787 \times 10^{-6}) P^{-1.6055} E^{2.1446} , \qquad (IV.6)$$

which when expressed with P on the left-hand side as in (IV.6) becomes:

$$P = (.6266 \times 10^{-4}) Q^{-.6229} E^{1.3357} \qquad (IV.7)$$

This form gives rise to a hyperbolic relationship between P and Q at each level of the shift variable, E. This demand curve is shown in Figure IV.1 and has the property that the price elasticity of demand is constant and in this case equals -1.6055.

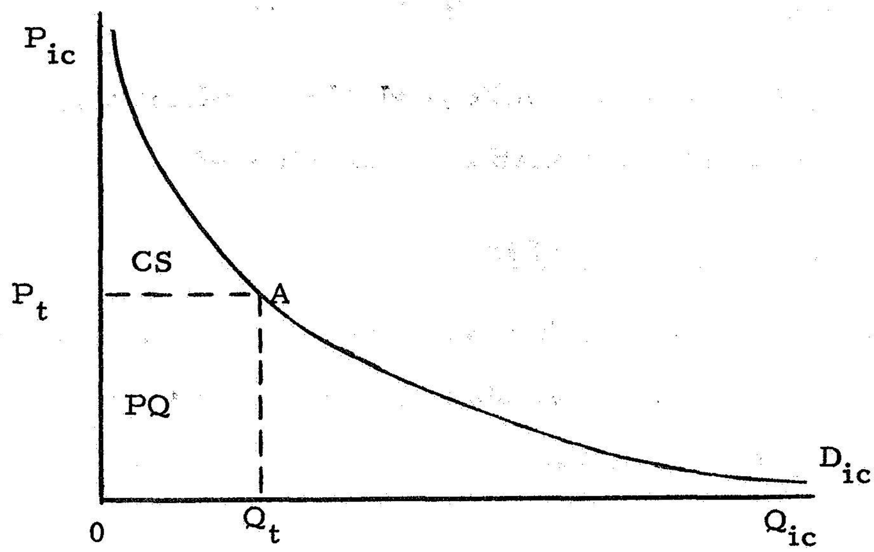


Figure IV.1

Now, in order to calculate the value of CS in year t, the value of $i_t = \alpha E^{\gamma} = (.6266 \times 10^{-4})(E_t^{-1.3357})$ was calculated to obtain the level of demand where

$$P_t = i_t\, Q_t^{-.6229} \qquad \text{(IV. 8)}$$

By integrating (IV. 8) with respect to Q_t and evaluating from zero to Q_t for year t, the area Y_t under the demand curve from zero to Q_t at this point in time was determined:

$$Y_t = \int_0^{Q_t} P(Q)dQ = \left[\frac{a}{\beta + 1} E^{\gamma}\right] Q^{\beta + 1} \Big|_0^{Q_t} = \frac{i_t}{\beta + 1} Q^{\beta + 1} \Big|_0^{Q_t} \quad \text{(IV. 9}$$

or

$$\int_0^{Q_t} P(Q)dQ = \frac{i_t}{.3771} Q_t^{.3771} \Big|_0^{Q_t} = (.661 \times 10^{-3})\, E_t^{1.3357} \quad \text{(IV. 1}$$

$$Q_t^{.3771} \Big|_0^{Q_t} = Y_t$$

Of course, the value of Y_t overstates CS_t by the amount of integrated circuit sales in that year. Thus,

$$CS_t = Y_t - (PQ)_t . \quad \text{(IV. 11)}$$

In terms of Figure IV. 1, Y_t is represented by the entire area under the demand curve from 0 to Q_t. CS_t is then depicted by the area under the curve above the broken line connecting points P_t and A. This indicates the amount by which the consumers' valuation of Q_t, or Y_t, exceeds the amount paid for Q_t, or $(PQ)_t$.

Before going any further it should be noted that calculation of CS using (IV. 11) directly might overstate secondary benefits. This would be so because NASA has purchased integrated circuits in each of the sample years and total benefits so measured would include any benefits that NASA itself derived. Since there is some question as to whether these should

be considered "secondary" benefits, an attempt was made to exclude from the calculations NASA's demand for, and, consequently, their benefits from integrated circuits. It should also be noted that no attempt was made to eliminate benefits to other government agencies such as the Defense Department, who, together with NASA, represented a large portion of early years' purchases of integrated circuits. The rationale for leaving in the other agencies purchases is that they were, in fact, not directly related to NASA's activities.[9]

Since a precise sorting out of NASA's demand for integrated circuits would be an extremely involved task, it was assumed that NASA's demand was completely inelastic. Thus, subtracting out NASA's share of the market would have the effect of shifting the demand curve inward by the extent of its share of total purchases in each year.[10] If λ_t = NASA's share in year t, then CS is calculated by evaluating the integral in (IV.10) from $\lambda_t Q_t$ to Q_t and subtracting $(1 - \lambda_t)(PQ)_t$ from γ_t in (IV.11), or[11]

$$CS_t = \frac{i_t}{\beta + 1} \; Q_t^{\beta + 1} \Bigg|_{\lambda_t Q_t}^{Q_t} - (1 - \lambda_t)(PQ_t) \qquad \text{(IV.12)}$$

Consumers' surplus was calculated using equation (IV.12) adjusted for NASA purchases for each of the years in the sample, i.e., 1963 to 1972, inclusive.

The calculation of values for CS up to ten years beyond the last sample year involved essentially two steps. In the first step, future values of the shift variable E_t were developed by regressing E_t on a linear time trend. This yielded

$$\hat{E}_t = 16366 + 1209\,(t - 1962)$$

where $t = (1963, \ldots, 1972)$.

Projected values for expenditures $\hat{E}_{1972+s}$ were then calculated, where $s = (1, \ldots, 10)$.

Next, making the conservative assumption that integrated circuit prices remain at their 1972 level, the future values of CS were calculated using the projected E values. The values of CS_{1963} to CS_{1982}, expressed in 1974 constant dollars, appear in Table IV.1. Again, the values in this column represent the undiscounted level of total benefits realized in each of the years from a decrease in the price and an increase in the use of integrated circuits.

C. Assignment of Benefits to NASA

1. Chronology of Developments

Although it is difficult to pinpoint the origins of integrated electronics, certainly the requirement for miniature electronic systems during World War II led to the development of many of th^ fundamental ideas and

Table IV. 1

Consumers' Surplus: Total Benefits

(Millions of 1974 $'s, Undiscounted)

Year	Total Benefits CS 1974 Million $'s
1963	22
1964	29
1965	66
1966	135
1967	297
1968	453
1969	652
1970	615
1971	727
1972	990
1973	1243
1974	1354
1975	1471
1976	1592
1977	1719
1978	1850
1979	1987
1980	2129
1981	2277
1982	2430

techniques. Following the war, three scientists at Bell Laboratories, William Shockley, John Bardeen, and Walter Brattain, began studying field-effect amplification in germanium. Their studies of surface-contact potentials and the space-charge layer led to the invention of the point-contact transistor in 1947; for the first time, there was a practical solid state device capable of amplification. The point-contact transistor was succeeded in 1948 by the junction, or bipolar, transistor, which was easier to manufacture. During this period, considerable progress was made in miniature batch interconnection techniques, among them the successful use of etched circuits.

Under Shockley's leadership, interest in the field-effect remained high. Shockley published the theory of the field-effect transistor in 1952, and a practical form using a germanium substrate was built the following year. During the 1950's, silicon began to replace germanium as a transistor material because silicon remains stable over a greater temperature range and so promised to bring better manufacturing control and lower costs. A body of knowledge about the surface properties of silicon as well as reproducible techniques for the fabrication of stable structures developed. Texas Instruments Corporation is credited with the **invention** of the integrated circuit in 1961. Incorporating the concept of a silicon structure in which an insulated field plate, or gate, is used to induce a conducting surface channel between two surface positive-negative (p-n) junctions, a silicon field-effect transistor was demonstrated by RCA in 1962. This structure utilized a gate electrode of metal separated from the silicon base by an insulator, usually of silicon dioxide.

In November, 1962, NASA launched integrated circuits into space for the first time. This was followed in 1964 by the first space application of the p-channel enhancement type MOS transistor (PMOS). The successful operation of these devices effectively demonstrated the reliability of integrated circuits to the commercial marketplace.

The 1960's were a time of great progress in research and development in integrated circuitry. In 1963, NASA opened its Electronics Research Center in Massachusetts which, in its six-year operational lifetime, spearheaded a great number of developments in integrated circuits. Almost all of the other NASA research centers were also engaged in microelectronics research. Another government agency responsible for a great deal of work in microelectronics has been the U.S. Air Force. Additionally, many commercial interests were researching and producing integrated circuits. Prominent among these have been Western Electric's Bell Laboratories, RCA, Westinghouse, Texas Instruments, American Micro-Systems, Inc., Fairchild Camera and Instruments, Philco-Ford, Hughes Semiconductor, Harris Semiconductor, IBM, Motorola, and Martin Marietta Corp.

Much of the work in microelectronics of the past decade produced greater refinements in batch-processing techniques and increased miniaturization of devices, making possible large-scale integration. This led to widespread commercial applications in the 1970's. The first commercial application of the PMOS transistor, in 1969-70, appeared

in the form of juke box controls produced by American Micro-Systems, Inc. Today, almost every electronic device designed incorporates some form of MOS circuitry. Probably the largest single commercial application of MOS circuits in the last few years has been in desk and pocket calculators, introduced in 1972. MOS circuits are also widely used in watches and clocks, hearing aids, mechanical seat belt signal devices, and electronic organs.

2. Speed-Up Due to NASA

Because the size and weight, as well as reliability, of electronic devices have been of crucial importance to NASA's space missions, NASA was an important pioneer user of integrated circuits and has been actively engaged in microelectronics research. Through its own research centers and through subcontracts, NASA has certainly made significant contributions in this field, contributions which in some instances have led to earlier development and application of advanced technology than would otherwise have been the case. This is especially true insofar as NASA's specification requirements are far more stringent than those of other government agencies or of industry. NASA has, in effect, forced the development of circuits with ever greater degrees of integration and reliability. Among the specific areas to which NASA has contributed are computer-aided design and testing, development of PMOS and CMOS transistors, fabrication techniques, and reliability and testing procedures.

In attempting to identify a specific speed-up time to associate with NASA's contributions, experts in the integrated circuit field having no

connection with NASA were asked to estimate the probable amount of time that NASA R&D has sped up technological development in integrated circuitry. The five experts' estimates were as follows: [11]

0	Years
1 - 1.5	Years
2	Years
2-3	Years
3	Years

In the calculations of benefits due to NASA, speed-up times of 1/2 year, two years, and three years were used. They will be referred to as the minimum, probable, and maximum speed-ups.

Evidence bearing on NASA's contribution was also obtained from a survey of experts conducted by the Denver Research Institute. For integrated circuits, it was estimated that 20 percent of the advancements would not have occurred without NASA contributions, 72.5 percent have occurred earlier than otherwise due to NASA, and 7.5 percent have occurred due to parallel contributions of NASA and others. [12]

3. Benefits Attributable to NASA

Table IV.2 summarizes the benefits attributable to NASA, calculated for two time periods: from 1963 to 1982, and from 1963 into perpetuity. The method for projecting benefits through 1982 was described in Section B of this chapter. Under the speed-up assumptions, the same benefits would accrue in the absence of NASA contributions, only the benefits would appear one-half year, two years, or three years later, depending on which speed-up

estimate is used. The difference between the benefit stream that occurs with NASA's influence and the benefit stream that would appear later without NASA's influence represents the share of the total benefits which is attributable to NASA.

These benefits were estimated for every year in the decade following 1972, the last year for which data are available; benefits were then discounted to obtain present value, and totaled. Also, recognizing that benefits associated with integrated circuits will probably continue to be realized beyond 1982, a second computation of benefits was performed, using the assumption that the stream of benefits will continue into perpetuity. The results, presented in Table IV.2, indicate a sizable contribution by NASA to the benefits from integrated circuits.

D. Summary

In this case study, integrated circuits have been treated as a new product, because they represent a significant advance both in technology and in new applications for which the use of discrete electronic elements is not feasible. A demand curve was estimated directly, allowing the quantification of benefits in terms of the consumers' surplus area under the demand curve at each point in time.

Using 1974 constant dollars, the stream of benefits which can be attributed to NASA was calculated for the years from 1963 to 1982 and from 1963 to perpetuity, under three conditions of speed-ups. When expressed in present value terms, and assuming a 2-year speed-up, the benefits from

Table IV.2

Benefits From Integrated Circuits Attributable to NASA

(Millions of 1974 $'s, Present Discounted Value)

Years	3 - Year Speed-Up		2 - Year Speed-Up		1/2 - Year Speed-Up	
	5% Discount Rate	10% Discount Rate	5% Discount Rate	10% Discount Rate	5% Discount Rate	10% Discount Rate
1963-1982	$ 6,887	$7,277	$4,740	$5,080	$1,239	$1,349
1963-Perpetuity	$12,875	9,340	8,753	6,463	2,260	1,701

1963 to 1982 amount to $4,740 million or $5,080 million, depending on whether a 5 percent or 10 percent discount rate, respectively, is used. Under the same assumption of speed-up, the present value of benefits from 1963 to perpetuity amounts to $8,753 million, or $6,463 million, using 5 percent and 10 percent discount rates, respectively.

FOOTNOTES - CHAPTER IV

1. These circuit elements are usually microscopic in size and as a result, integrated circuits are often referred to as microcircuits.

2. When these circuit types are used in combination, the combinations are known as hybrid integrated circuits.

3. A semiconductor is a material which has electrical conductivity greater than that of an insulator and less than that of a good conductor, e.g., metal.

4. The New York Times, December 8, 1974, Section 3, p. 1.

5. William C. Hittinger, "Metal-Oxide-Semiconductor Technology," Scientific American, Vol. 229, No. 2, August, 1973, pp. 53-54

6. A few comments are in order with regard to the specification of the supply equation. A form of the model was fit which specified the supply price to be a function of output and the prices of labor and capital as called for in equation (IV.2). Unfortunately the signs of both input price coefficients were negative, thus suggesting that the equation was misspecified or that there was a serious errors-in-variables problem. The solution was to specify price as a function of the average cost of materials (ACM) and the average cost of labor (ACL). ACL is equal to WL/Q , a form which captures the interactive effect of the wage rate and the average productivity of labor on the price of output. During the period 1963-1972, P_{ic} steadily decreased and w , as measured, steadily increased. ACL allows for the possibility that average productivity also increased sufficiently to overshadow the trend in w . This is evidently what took place because the coefficient of ACL was positive. This means that even though an hour of labor cost more, labor was combined with other factors in a technologically more efficient way. The same procedure would have been used with an average cost of capital, defined in the same way, if a reasonable capital "bill" had been available.

7. John Tilton, The International Diffusion of Technology: The Case of Semiconductors (Washington D. C.: The Brookings Institution, 1971), pp. 85-89. Tilton states, "So far in the young semiconductor industry's history, economies of scale have not been great, and learning economies, though appreciable, have continually been wiped out by technological change. As a result, new firms have successfully entered the industry without huge outlays of capital.", (p. 87).

8. The initial estimation of the supply equation yielded:

$$\text{Supply: } \ln P = \underset{(17.7144)}{.9919} + \underset{(2.7908)}{.4898} \ln ACM + \underset{(3.2777)}{.5196} \ln ACL$$

$$\bar{R}^2 = .9983 \quad F_{2,7} = 2669.9 \quad DW = 1.171$$

As indicated by the t-statistics, the coefficients are significantly different from zero at the 95 percent confidence level, and the overall fit is good, as revealed by the relatively high values of $\bar{R}^2$ and F. However, the null hypothesis of no serial correlation could be rejected on the basis of the calculated DW statistic. The procedure adopted to correct for this problem was the Cochrane-Orcutt Iterative Technique* of solving for the serial correlation coefficient.

The corrected supply equation, in which the solution for Rho converged after four iterations, is

$$\ln P_t - .4174 \ln P_{t-1} = \underset{(13.5828)}{.9929} + \underset{(2.1561)}{.4659} (\ln ACM_t - .4174 \ln ACM_{t-1})$$

$$+ \underset{(3.0012)}{.5419} (\ln ACL_t - .4174 \ln ACL_{t-1})$$

$$\bar{R}^2 = .9977 \qquad DW = 1.489$$

According to the DW, the null hypothesis could not be rejected and the fit values of lnP may now be used in estimating the demand equation. (*See D. Cochrane and G. H. Orcutt, "Application of Least-Squares Regressions to Relationship Containing Auto-Correlated Error Terms," Journal of the American Statistical Association, Vol. 44 (1949), pp. 32-61.)

9. There is, of course, another difficulty in that the proof of the validity of measuring benefits in terms of areas under demand curves for intermediate products assumes cost minimizing and profit maximizing firms. If the government agencies violate these rules, the proofs in Appendix A would not apply. However, it is difficult to assess just what affect such violations would have.

10. Assuming complete inelasticity is conservative in that it results in a smaller non-NASA CS area than if a more elastic demand curve was assumed. If we were to take this procedure one step further and subtract out all government purchases in this way -- a procedure of questionable validity -- then the resulting benefits due to NASA would fall by 50-60 percent.

11. An estimate of five years was also obtained, but was excluded when a follow-up call indicated that the individual could not explain and would not defend his guess.

12. Denver Research Institute, Mission-Oriented R&D and the Advancement of Technology, a report to NASA, May 1972.

CHAPTER V:

NASTRAN

(Computer Assisted Structural Analysis)

CHAPTER V:
NASTRAN

A. Introduction

1. Brief Description of Technology

NASTRAN (NASA Structural Analysis) is a general purpose, finite element computer software package for static and dynamic analysis of the behavior of elastic structures under a wide range of loading conditions. NASTRAN is aimed primarily at large problems involving many degrees of freedom and is capable of treating problems of virtually unlimited size. Industry users are generally product engineers (or other specially trained technicians) in mechanical or civil engineering applications such as aircraft and automobile production, bridge construction, or power plant modeling.

The structure to be analyzed is approximated by an array of elastic finite elements, each of which is characterized by an appropriate set of sectional properties and material properties. The NASTRAN element library currently contains over 30,000 one-, two-, and three-dimensional elements, including several non-linear elements. Although other structural analysis software packages are available, there are almost none which are capable of performing such large-scale analysis as NASTRAN, or which are generalizable to as many applications.

2. Nature of Benefits Generated

There are various costs and benefits accruing to the NASTRAN user. The program and documentation are sold at a price meant simply to cover NASA's selling costs (an average of $1,700, depending on options required). Start-up expenses include training personnel in use of the program and access to adequate computer facilities, generally including an interactive graphic display. These costs are usually compensated for by considerable savings in operating expenses over the other methods available to the firm.[1/] In addition, NASTRAN may provide the user with new capabilities. These benefits are enhanced by ongoing maintenance and research, which has led to several improved versions since 1970.

B. Measurement of Benefits

1. Methods Applied

It was felt that the best approach to measuring the benefits of NASTRAN, which, as noted, is used in a wide variety of industries and enters a firm's production process in complex ways, would be to survey those firms thought to be using the program. The specifics of the survey approach are described in detail below.

2. Data Sources

Estimates of cost savings due to NASTRAN were obtained from telephone interviews with a sample of users. Each person from a 16 percent random sample of a list of 281 discrete departments, agencies, and firms[2/]

receiving a NASTRAN newsletter was contacted and questioned on the use of NASTRAN by his group, division, or firm, depending on which level was specified in the newsletter mail listing. Respondents were asked the following questions in an unstructured interview:

1) When did you first start using NASTRAN?

2) What type of start-up costs were incurred?

3) How frequently do you run a job on the average?

4) What is your estimate of the annual (or per job) cost savings realized from using NASTRAN instead of the best alternative (i.e., what you would use if NASTRAN were not available)?[3/]

Using an original random sample of 47 names plus a randomly selected back-up list of 13 names, 45 responses were obtained,[4/] which broke down as follows. (Where the user is a consulting firm, benefits are not cost savings, but are realized as profit from business generated because of the availability of NASTRAN. In such cases, an estimate was obtained of the revenue generated from using NASTRAN, and 20 percent of this was taken as an estimate of the benefits.)

<u>Survey Response</u>

22 - gave quantitative estimates of annual cost saving.

6 - reported that savings were obtained but could give no quantitative estimate.

2 - reported that no savings were obtained.

2 - were new users; no benefits realized until 1975.

13 - were not users.

3. <u>Results of Estimation</u>

The range of respondents' estimations of annual savings is considerable, as indicated in Table V.1. (Although the $12,000,000 may seem to be

Table V.1

Annual Savings From Use of NASTRAN

Savings ($/Year)	Number of Users	
	Respondent Sample	Newsletter Population Projection
0-50,000	13	81
100,000-1,000,000	6	37
2,000,000	1	6
3,600,000	1	6
12,000,000	1	6

an extreme value, there is published documentation that at least one other firm, not included in our sample, has realized similar cost savings from the use of NASTRAN. [5] Therefore, it was decided that this estimate is a valid one; it has accordingly been included in all computations.)

In order to derive the total benefits realized within the newsletter population from use of NASTRAN, the number of respondent firms (including those giving no quantitative estimate of savings and those reporting no savings) which adopted NASTRAN in each year since it has been available was tabulated. This information is given in Table V.2. By far the largest

Table V.2

Adoption of NASTRAN

Year	No. of Adopters: Respondent Sample (n=32)*	No. of Adopters: Population Projection (n = 199)	Years of Use
1971	7	44	4
1972	7	44	3
1973	14	87	2
1974	2	12	1
1975	2 (new users)	12	0

* Including the two users who did not realize cost savings.

proportion of respondents first began using NASTRAN in 1973, and have been using it for two years.

Once the NASTRAN users were grouped according to numbers of years of use, the annual cost savings estimates were tabulated for each group. For the six firms which could not provide quantitative estimates of savings, the average annual cost savings estimated by the other users ($840, 595. 80) were attributed to them. The two new users, who will not realize cost savings until the end of 1975, were also attributed the average cost savings. These cost savings totals are shown in Table V. 3.

Using the assumption that respondent firms realize these cost savings in every year during which NASTRAN is used, cumulative totals of annual savings were computed. In other words, the savings for each year equal the savings for users who adopted that year plus the savings for those who adopted in previous years.

Table V.3

Annual Savings By Year Of Adoption

(000's 1974 $'s)

Year	Respondent Sample (n=32)	Population Projection (n = 199)
1971	6,711	41,876
1972	13,044	81,395
1973	5,393	33,652
1974	70	437
1975	1,681	10,489

In addition, start-up costs incurred in adopting NASTRAN must be deducted from cost savings to get net benefits. All users were attributed start-up costs in their first year of use. Three kinds of start-up costs were identified. The purchase of the program from NASA for $1,700 is included here. Training engineers in the use of the program was accomplished in most cases by attendance at a one or two week course, often taken by several engineers in the firm. Also, some cost is incurred in computer programming to adapt the NASTRAN program to the user's system and data base. Most respondents were unable to provide estimates of actual start-up costs; however, the training and programming estimates used here reflect the average manpower allocations indicated by respondents. A figure of $1,250 was used to reflect the cost of training, representing one engineer-month. A similar estimate of $1,250 was used to represent one programmer-month on the programming task. The

purchase of computer hardware was not included as a start-up cost. Occasionally, a firm did acquire new hardware during the time it was using NASTRAN, but it was assumed that the equipment would have been obtained anyway and was not attributable solely to NASTRAN use. Thus, the start-up costs for each user were taken to be $4,200.

Table V.4 shows the cumulated annual savings and the cumulated net benefits, defined as total savings minus each year's start-up costs, for the sample of respondents and for the projected user population.

Table V.4

Preliminary Calculation of NASTRAN Benefits

(000's 1974 $'s)

Year	Cumulated Annual Savings, Respondent Sample (n=32)	Cumulated Net Benefits, Respondent Sample (n=32)	Cumulated Net Benefits, Population Projection (n = 199)
1971	6,711	6,681	41,691
1972	19,755	19,725	123,086
1973	25,148	25,091	156,568
1974	25,218	25,210	157,307
1975	36,899*	26,891	167,798

* This figure includes average cost savings attributed to the two new users.

4. Calculation of Total Benefits

Since NASTRAN was first made available in 1971, there are benefits data for only four years. It seems reasonable to expect that the program will continue to yield benefits in the future, and calculations were made using that assumption. Specifically, it was assumed that: (1) those using

NASTRAN in 1974 receive the same benefit in each year from 1975 to 1984 that was received in 1974, with the exception of the two new users, who were assigned, for the years 1975 through 1984, the average cost savings; and (2) there will be no new users of NASTRAN in the years 1975 to 1984. This latter assumption was adopted to provide a lower bound on calculated benefits. Table V.5 presents the calculations of total net benefits from NASTRAN for the 1971-1984 period, for both the respondent sample and the projected user population.

Table V.5

Estimated Net Benefits, 1974-1984

(000's 1974 $'s)

Year	Respondent Sample (n=32)	Population Projection (n = 199)
1971	6,681	41,691
1972	19,725	123,086
1973	25,091	156,568
1974	25,210	157,307
1975	26,891	167,798
1976	26,899	167,850
1977	26,899	167,850
1978	26,899	167,850
1979	26,899	167,850
1980	26,899	167,850
1981	26,899	167,850
1982	26,899	167,850
1983	26,899	167,850
1984	26,899	167,850

C. Assignment of Benefits to NASA

1. Chronology of Development

The finite element approach to structural analysis has been developed in the last twenty years. There are other finite element software packages that have appeared during this time period. They typically differ from NASTRAN in the following respects: small problem orientation, relatively few finite elements, limited dynamics capability, or specialized application possibilities.

Before NASTRAN, another general finite element NASA program, SAMIS (Structural Analysis and Matrix Interpretative System), was available to industry users. Perhaps due to its development by modification and extension, SAMIS was fraught with errors that were frustrating and time-consuming, thereby limiting its usefulness. Furthermore, some users required increased capability, particularly for dynamics problems.

Between 1965 and 1970, Goddard Space Flight Center developed NASTRAN through a combination of in-house and contracted research for approximately $3,000,000. It was released to public users in November, 1970, and, in general, overcame the stated shortcomings of SAMIS. NASA now spends about $400,000 annually to maintain and improve NASTRAN.

2. Speed-Up Due to NASA

In considering NASA's contribution to the development of NASTRAN, the issue of speed-up time is confronted in a somewhat different form than in the previous case studies. Since NASA was directly responsible for NASTRAN's development, there is a temptation to attribute the entire benefits stream to NASA. However, consistency with the approach in other

case studies requires recognition of the indirect contributions of others to the development of the technological base on which NASA built; therefore, the theoretical possibility was accepted that a similar program eventually would have been developed by others if NASA had not developed it.

How much longer would it have taken to develop such a program without NASA? NASTRAN, as noted previously, was the result of an intensive development effort over a number of years, and the costs were considerable. According to three non-NASA computer software programmers familiar with NASTRAN, the costs would have been prohibitively high for an individual firm. An individual firm would have had to market the innovation in order to realize a profit; the interest in such activity in firms typically using NASTRAN is probably not high. Theoretically, an entrepreneur might have had sufficient incentive and ability to attempt to develop and market a similar program; however, the software experts contacted doubted the likelihood of any such activity without NASA. These experts felt that without NASA, a similar program would not yet have been developed and would not be likely to be developed. However, to be conservative it was assumed simply that to date there would not have been a NASTRAN. In other words, an estimate of four years was taken as both the minimum and probable speed-up attributable to NASA's contributions to NASTRAN. The maximum speed-up estimate was arbitrarily assumed to be ten years; this figure was assumed solely for illustrative purposes, as the actual maximum estimates were for what amounts to an infinite speed-up.

3. Benefits Attributable to NASA

Table V.6 shows the benefits from NASTRAN that are attributable to NASA as the difference between the actual benefits stream and the same benefit stream appearing four years later. The same process was

repeated for the case of the maximum speed-up, with the benefits stream appearing ten years later. Since it was assumed that there are no new NASTRAN users after 1975 and that old users continue to receive the same benefits in future years, the elements of the NASA benefits stream under the four-year speed-up condition are all zero after 1979. Thus, the benefits in this case are equal to those that would be calculated in the case of projections into perpetuity.

Table V.6

Benefits Attributable to NASA

(000's 1974 $'s)

Year	Cumulative Net Benefits Population Projection	Net Benefits With Four-Year Delay	Net Benefits Attributable to NASA
1971	41,691	--	41,691
1972	123,086	--	123,086
1973	156,568	--	156,568
1974	157,307	--	157,307
1975	167,798	41,691	126,107
1976	167,850	123,086	44,765
1977	167,850	156,568	11,294
1978	167,850	157,307	10,543
1979	167,850	167,798	52
1980	167,850	167,850	--
1981	167,850	167,850	--
1982	167,850	167,850	--
1983	167,850	167,850	--
1984	167,850	167,850	--

4. Calculation of Cost-Benefit Ratios

Unlike the other fields included in this report as case studies, records of NASA expenditures on NASTRAN were readily available. To provide additional information on the economic returns on NASA's investment in NASTRAN, cost-benefit ratios were computed.

In order to calculate the cost-benefit ratio of NASA's investment in NASTRAN, costs, defined as NASA expenditures on NASTRAN, were obtained for each year since 1966, the first year of NASTRAN development. It was assumed that expenditures from 1975 to 1984 will be for maintenance only; to control for advances in technology reflected in improved versions of the program, development costs are not added in. Thus, the estimated future expenditures on NASTRAN are $260,000 yearly, which is the amount spent on maintenance alone in 1974. NASA expenditures on NASTRAN are shown in Table V.7..

Measurement of cost-benefit ratios is based on the analysis of two time series: estimated costs and benefits for 1966 to 1984; and estimated costs and benefits for 1966 into perpetuity. Costs refer to NASA expenditures, and benefits refer to the users' net benefits attributable to NASA. Before calculating the cost-benefit ratios, both NASA expenditures and net benefits were expressed in present value terms; discount rates of 5 percent and 10 percent were used in these calculations.

Table V.8 shows, for 1966 through 1984 and for 1966 into perpetuity the costs, benefits, and cost-benefit ratio of NASA investment in NASTRAN. All figures are in 1974 dollars.[6]

Table V.7

NASA Expenditures on NASTRAN

(000's 1974 $'s)

Year	Amount	Year	Amount
1966	1,122	1975	260
1967	912	1976	260
1968	676	1977	260
1969	741	1078	260
1970	718	1979	260
1971	697	1980	260
1972	658	1981	260
1973	592	1982	260
1974	450	1983	260
		1984	260

Table V.8

Summary of Costs and Benefits* of NASTRAN

	Four-Year Speed-Up		Ten-Year Speed-Up	
	5 Percent Discount Rate	10 Percent Discount Rate	5 Percent Discount Rate	10 Percent Discount Rate
1966-1984				
Costs (Millions, 1974 $'s)	10.3	12.0	10.3	12.0
Benefits (Millions, 1974 $'s)	684.6	701.2	1,491.1	1,359.1
Benefit-Cost Ratio	66.6	58.2	145.0	112.9
1966-Perpetuity				
Costs (Millions, 1974 $'s)	13.5	13.0	13.5	13.0
Benefits (Millions, 1974 $'s)	684.6	701.2	1,491.2	1,359.1
Benefit-Cost Ratio	50.8	53.8	110.7	104.2

* Costs - refer to NASA expenditures on NASTRAN.

Benefits - refer to net benefits, to users, which are attributable to NASA.

D. Summary

A sample of NASTRAN users was questioned on estimated cost savings over using the best alternative for structural analysis. From these, population estimates were computed and projected. NASA expenditures on NASTRAN were obtained and likewise projected

The present value of benefits and cost-benefit ratios were calculated and reported in Section C. They indicate that the benefits due to NASA's investment in NASTRAN are probably on the order of $700 million dollars, and the benefit-cost ratio is probably greater than 50.

FOOTNOTES - CHAPTER V

1. Other methods include: a) another software package
   b) analytic calculations
   c) testing and prototype building.

2. The original mailing list contains 521 names. After eliminating recipients from NASA, from libraries and universities, and from foreign countries, as well as eliminating duplications of recipient locations, the newsletter recipient population numbers 281.

3. In at least one case the respondent argued that there was absolutely no alternative means -- short of developing a software program like NASTRAN -- of performing some of the tasks now done with NASTRAN. In such a case the respondent was classified as unable to provide an estimate.

4. The others on the list could not be contacted within the time frame of our efforts.

5. NASTRAN Benefits Analysis, Vol. 11, Final Technical Report. Computer Sciences Corporation, Falls Church, Virginia, February, 1972, p. 3-19.

6. The internal rate of return for a four-year speed-up is equal to 138 percent.

CHAPTER VI:

CONCLUSIONS AND IMPLICATIONS

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CONCLUSIONS AND IMPLICATIONS

A. Review of Objectives

The purpose of this study was twofold: 1) to develop procedures for quantifying the economic benefits of secondary applications of NASA technology; and 2) to make preliminary applications of these procedures. This final chapter summarizes and assesses the efforts to meet these goals and considers briefly the implications of the study results.

B. Methods of Estimating Benefits

Chapter I outlines an approach to estimating the benefits of secondary applications of NASA technology. The validity of the approach can be judged essentially on the basis of answers to two questions: 1) is the approach theoretically sound? and 2) is it useful in generating estimates?

The theoretical foundations of the approach derive in essence from two subsets of the economics literature: that dealing with cost-benefit analysis and that dealing with technological change. The techniques of measuring total benefits are based on well accepted practices of cost-benefit analysis. To facilitate the efforts to measure the benefits of advances directly affecting intermediate goods, a modest extension of the literature was offered.

In assigning benefits to NASA, a widely accepted theoretical view of the research process was practically implemented. The view holds that any one contributor's contribution to technological advance is to "speed up" the process. While implementation necessitated analytical simplifications, NASA's role was generally interpreted in a conservative manner.

With regard to the usefulness of the methods in generating estimates, the results essentially speak for themselves. Quantitative estimates were derived for four case studies. However, there was considerable difficulty in collecting the requisite data, and at least two other attempted case studies were not completed because of lack of data. 1/ On the other hand, given sufficient resources for data collection, the method could deal with a variety of forms of technological advance.

C. Results of Preliminary Application of the Methods

The study estimated economic benefits for four technologies: cryogenic multilayer insulation, gas turbines in electric power generation, integrated circuits, and computer-assisted structural analysis (NASTRAN). The procedures for estimating the total benefits of the technological advances were highly conservative. In assessing NASA's contribution, twelve possibilities were generally considered: a minimum, a maximum, and a conservative probable speed-up, each with projections of benefits into the future for ten years (beyond the last data year) and into perpetuity, and each of these employing discount rates of 5 and 10 percent. These various possibilities were presented to illustrate the range of possible benefits due to NASA.

Depending on whether one adopts the more or less conservative figures from the values presented, the total benefits due to NASA can range from about $2,000 million to $17,000 million. Given the innovative nature of the work and the uncertainties involved, it is difficult to argue with great conviction that one number is significantly better than the others. However, it would seem that a reasonable choice would be the estimates based on the "probable" speed-up, using a 10 year projection and a 10 percent rate of discount. This choice, the figures for which are presented in Table VI. 1, yields a total benefits figure of approximately $7,000 million.

D. Conclusions

In interpreting the results of this study, one should keep clearly in mind its limitations. There are, of course, the conceptual and practical limitations of any cost-benefit analysis. However, the NASA-benefits estimates, which are among the first of their kind ever made, should be recognized as especially rough. For one thing, they are sensitive to parameter estimates derived from various statistical procedures, which were rigorously carried out but which, in cases such as integrated circuits, were performed with limited data. For another thing, they rely in part, via the "speed-up" assumptions, on opinions.

Despite their limitations, it would seem that, because of the rigor with which the analysis was performed and the care with which a policy of conservatism was employed, the "probable"

Table VI.1

Results of Benefits Estimation

Technology	Interval of Benefits Estimation	Estimated Probable NASA Acceleration (Years)	Probable Benefits Attributable to NASA (Millions)
Gas Turbines	1969 - 1982	1.0	$ 111
Cryogenics	1960 - 1983	5.0	$1,054
Integrated Circuits	1963 - 1982	2.0	$5,080
NASTRAN	1971 - 1984	4.0	$ 701
Total	—	—	$6,946

estimates are as reasonable as can be hoped for and are probably not an overstatement. In addition, there are at least three qualitative conclusions one might draw:

1. Secondary benefits of NASA R& D can be measured.
2. These benefits are in some cases impressively large. (The $7,000 million for just these four cases is more than twice NASA's annual budget.)
3. Since the benefits may be large, a complete assessment of the benefits of any R&D effort should recognize and attempt to account for benefits of secondary applications.

It is hoped that the work here will serve as a useful step in what the Council of Economic Advisors to the President describes as the need "to show the benefits, costs, and processes associated with R&D." 2/

FOOTNOTES - CHAPTER VI

1. These include a study of batteries and of the rechargeable pacemaker.

2. Economic Report of the President, 1972, pp. 127-128. U.S. Government Printing Office, Washington, D.C.

APPENDIX A:

INTERMEDIATE GOODS AND CONSUMERS' SURPLUS

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INTERMEDIATE GOODS AND CONSUMERS' SURPLUS

I. Introduction

This appendix provides the basic rationale for interpreting cost savings measured in intermediate good (factor) markets as economic benefits per the definition in Chapter I. Specifically, it discusses the relationship between consumers' surplus in final good markets and the area under a factor, or intermediate good, demand curve above factor supply. This area is analogous to consumers' surplus and is designated here as SPF - "the surplus to producers employing the factor".

It is demonstrated how, under a variety of market structures, changes in SPF for a specific factor are related to changes in consumer surplus associated with final goods which use the factor in production. Certain results related to the theoretical findings in this appendix have been discussed in the literature.[1/] This appendix presents the extensions of the theory and their derivations in order to make explicit the assumptions and limitations of the procedure employed for estimating economic benefits.

II. Price Taking in Output and Factor Markets

The relationship between SPF and consumer surplus varies depending on the assumptions made about market structure. However, the cornerstone of the analysis is the case where there is "price taking" in both the input and output markets and the production of both the intermediate and final goods is characterized by "constant cost". Though these assumptions are necessarily restrictive and not altogether "realistic", they provide a useful starting point.

Consider a "competitive" industry, made up of many identical firms, with many additional firms ready to enter the market. Suppose the level of production in each firm depends on two factors l and k and the aggregate industry production is given by

$$Q = AL^{\alpha}K^{\beta}, \quad \alpha + \beta = 1 \tag{A.1}$$

where Q is industry output, L the industry quantity of l, and K the industry quantity of k. Furthermore, suppose industry members take the factor prices of l and k, w and r respectively, as given parameters.

These assumptions describe a constant cost industry whose supply function is infinitely elastic. If C is the industry total cost, then minimizing $C = wL + rK$ subject to $Q = AL^{\alpha}K^{\beta}$ will yield the industry cost function. Forming the Lagrangian $\mathscr{L} = wL + rK + \lambda(Q - AL^{\alpha}K^{\beta})$ the following necessary conditions obtain:

$$\frac{\partial \mathscr{L}}{\partial L} = w - \lambda A\alpha L^{\alpha-1}K^{\beta} = 0 \tag{A.2}$$

$$\frac{\partial \mathscr{L}}{\partial K} = r - \lambda A\beta L^{\alpha}K^{\beta-1} = 0 \tag{A.3}$$

$$\frac{\partial \mathscr{L}}{\partial \lambda} = Q - AL^{\alpha}K^{\beta} = 0 \tag{A.4}$$

The factor demand functions and industry cost functions implied by cost minimization are:

$$L = A^{-1} \left(\frac{r\alpha}{\beta w} \right)^{1 - a} Q \tag{A.5}$$

$$K = A^{-1} \left(\frac{r\alpha}{\beta w} \right)^{-a} Q \tag{A.6}$$

$$C = A^{-1} \left(\frac{r}{\beta} \right)^{\beta} \left(\frac{w}{\alpha} \right)^{a} Q \tag{A.7}$$

where Q is the level of industry output.

To determine the level of industry output, a market demand must be introduced. Suppose that the linear equation (A. 8) describes market demand.

$$P = a - bQ \tag{A.8}$$

Now for given levels of w **and** r, **the following values obtain at equilibrium:**

$$Q^* = \frac{1}{b} \left[a - A^{-1} \left(\frac{r}{\beta} \right)^{\beta} \left(\frac{w}{\alpha} \right)^{\alpha} \right] \tag{A.9}$$

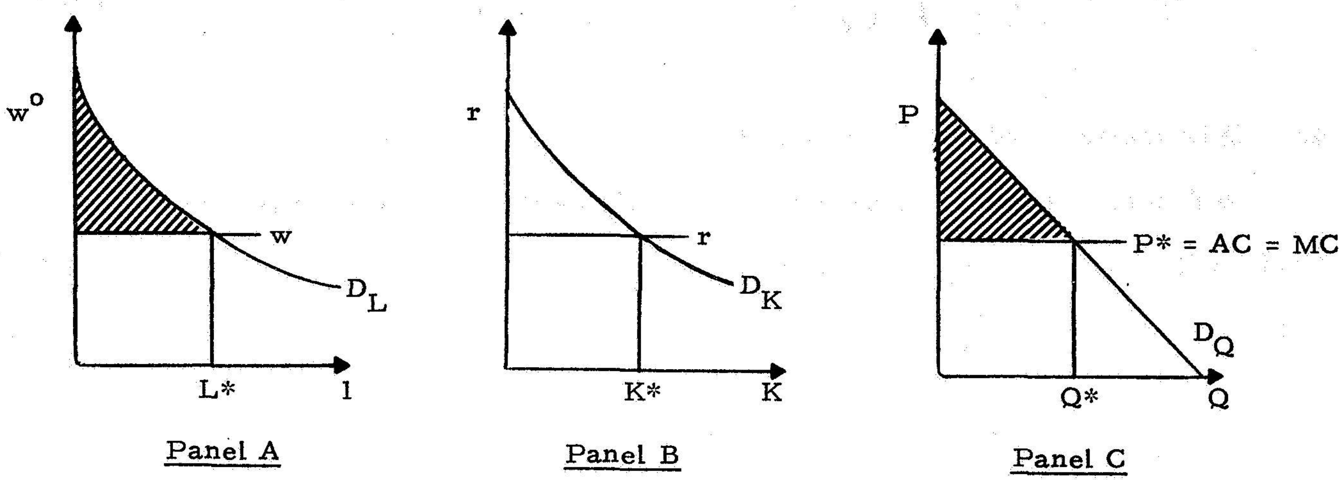
$$P^* = AC = MC = A^{-1} \left(\frac{r}{\beta} \right)^{\beta} \left(\frac{w}{\alpha} \right)^{\alpha} \tag{A.10}$$

$$L^* = A^{-1} \left(\frac{r\alpha}{\beta w} \right)^{1-\alpha} \frac{1}{b} \left[a - A^{-1} \left(\frac{r}{\beta} \right)^{\beta} \left(\frac{w}{\alpha} \right)^{\alpha} \right] \tag{A.11}$$

$$K^* = A^{-1} \left(\frac{r\alpha}{\beta w} \right)^{-\alpha} \frac{1}{b} \left[a - A^{-1} \left(\frac{r}{\beta} \right)^{\beta} \left(\frac{w}{\alpha} \right)^{\alpha} \right] \tag{A.12}$$

These are illustrated in Figure A.1, Panels A, B, and C.

Figure A.1



If the shaded area in Panel A is defined as factor l's SPF, then a basic result of this appendix can be easily stated: The shaded area in Panel A equals consumers' surplus -- the shaded area in Panel C. More formally,

$$\int_o^{L^*} D_L - wL^* = \int_o^{Q^*} D_Q - P^*Q^* \qquad \text{(A.13)}$$

The right hand side of (A.13) gives the consumers' surplus when output is Q* -- CS(Q*). A simple calculation yields

$$CS(Q^*) = \frac{1}{2b}\left[a - A^{-1}\left(\frac{r}{\beta}\right)^{\beta}\left(\frac{w}{\alpha}\right)^{\alpha}\right]^2 \qquad \text{(A.14)}$$

To evaluate the left hand of (A. 13), it is easier to work directly with equation (A. 11) which gives the quantity of 1 demanded for a given level of w and r. The equation depicted in Panel A is the inverse of the function in (A. 11) -- the usual diagramatics for demand curves.

Letting SPF(L*) stand for the 1's SPF when L is equal to L*:

$$\mathrm{SPF}(L^*) = \int_{w}^{w^0} \left\{ \left[\frac{1}{b}\, a\, \alpha^{\beta} A^{-1} \left(\frac{r}{\beta}\right)^{\beta} \right] x^{-\beta} - \left[\frac{1}{b\alpha}\, \alpha^{2\beta} A^{-2} \left(\frac{r}{\beta}\right)^{2\beta} \right] x^{1-2\beta} \right\} dx \qquad \text{(A. 15)}$$

where

$$w^o = \alpha \left[aA \left(\frac{r}{\beta}\right)^{-\beta} \right]^{1/\alpha} \qquad \text{(A. 16)}$$

The following describes the straightforward, but tedious, integration of (A. 15).

$$\int_{w}^{w^o} \left[\frac{1}{b}\, \alpha^{\beta} A^{-1} \left(\frac{r}{\beta}\right)^{\beta} \right] x^{-\beta}\, dx =$$

$$\frac{a^2}{b} - \frac{1}{b}\, aA^{-1} \left(\frac{r}{\beta}\right)^{\beta} \left(\frac{w}{\alpha}\right)^{\alpha} \qquad \text{(A. 17)}$$

and,

$$-\int_{w}^{w^{o}} \left[\frac{1}{b\alpha} \alpha^{2\beta} A^{-2} \left(\frac{r}{\beta}\right)^{2\beta} \right] x^{1-2\beta}\, dx = \tag{A.18}$$

$$- \frac{1}{2b} a^{2} + \frac{1}{2b} A^{-2} \left(\frac{r}{\beta}\right)^{2\beta} \left(\frac{w}{\alpha}\right)^{2\alpha}$$

Thus,

$$\mathrm{SPF}(L*) = \frac{a^{2}}{b} - \frac{1}{b} aA^{-1} \left(\frac{r}{\beta}\right)^{\beta} \left(\frac{w}{\alpha}\right)^{\alpha} - \frac{1}{2b} a^{2} + \tag{A.19}$$

$$\frac{1}{2b} A^{-2} \left(\frac{r}{\beta}\right)^{2\beta} \left(\frac{w}{\alpha}\right)^{2\alpha} ,$$

which upon simplification becomes

$$\mathrm{SPF}(L*) = \frac{1}{2b} \left[a - A^{-1} \frac{r}{b}^{\beta} \frac{w}{\alpha}^{\alpha} \right]^{2} \tag{A.20}$$

Comparison of equation (A.20) with equation (A.14) yields the fundamental equivalence between SPF and consumers' surplus under the assumed conditions. Specifically,

$$CS(Q^*) = SPF(L^*) \tag{A.21}$$

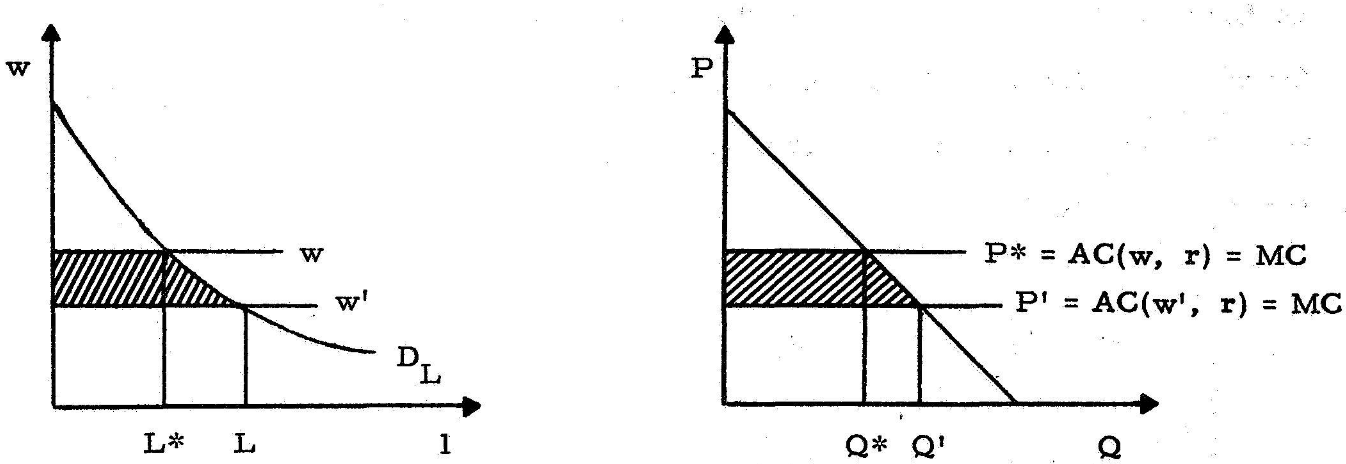
A similar result would hold for the other factor k.

To regroup, given the assumptions, the result in (A.21) states that at equilibrium the area under a factor demand curve is equal to the area under the demand curve for output. One interpretation of (A.21) is that if all other input prices and quantities were fixed, then the sellers of 1 could, through appropriate pricing strategies, capture the full value of consumers' surplus capturable by producers of output.

The assumptions upon which this result rests are by no means general. Presently, it is not clear how robust the results are. Linearity of output demand is probably not crucial, but the constant cost assumptions no doubt are. However, for many applications "constant costs" are reasonably descriptive. In particular, if both the factor market and output market are in a position of long run equilibrium, then competitive firms operate at the minimum point on their average cost curves where the relevant production parameters are approximately those of constant returns to scale.

Using (A.21) it is now possible to analyze how advances in technology which increase consumers' surplus are reflected in changes in SPF. To start, consider, under the above assumptions, the case where technology lowers the supply curve of l. Subsequently, the influence of market structure on the results will be discussed.

Suppose now that a technological change occurs which reduces the price of the factor l from w to w. Then the change in SPF for L -- indicated by the shaded area in Panel A of Figure A.2 -- will equal the change in the consumers' surplus -- the shaded area in Panel B.



Panel A

Panel B

This is so because, before and after technological change occurs, the relationship (A.21) must hold. That is,

$$CS(Q^*) = SPF(L^*)$$

and

$$CS(Q') = SPF(L')$$

Therefore,

$$CS(Q') - CS(Q^*) = SPF(L') - SPF(L^*) \tag{A.22}$$

Next, consider the case where the factor 1 is used in the production of more than a single output. The result is essentially unchanged. To see this, suppose there are several outputs Q_i, $i = 1, \ldots n$, for which the factor 1 is an input. Assume now that each of these industries is, in turn, described by a Cobb-Douglas production function with constant returns to scale, i.e.,

$$Q_i = A_i L_i^{\alpha_i} K_i^{\beta_i} \quad , \quad \alpha_i + \beta_i = 1, \quad i = 1, \ldots, n \tag{A.23}$$

From the above it is known that

$$SPF(L^*_i) = CS(Q^*_i) \qquad i = 1, \ldots, n \tag{A.24}$$

However, the factor demand is now the horizontal sum of the separate industry demand curves. Letting $L_i(w)$ be the i^{th} industry's demand for labor and $L(w)$ the total demand,

$$L(w) = \sum_{i=1}^{n} L_i(w) . \tag{A.25}$$

The factor 1's surplus is now given by

$$\int_{w}^{\infty} L(w)dw .$$

(Assume $L_i(w) = 0$, $w > w_i^o$). However, integration is additive, thus

$$\int_{w}^{\infty} L(w)dw = \int_{w}^{\infty} \sum_{i=1}^{n} L_i(w)dw = \sum_{i=1}^{n} \int_{w}^{\infty} L_i(w)dw . \tag{A.26}$$

But as

$$\int_{w}^{\infty} L_i(w)dw = CS(Q^*_i) , \tag{A.27}$$

then

$$\int_{w}^{\infty} L(w)dw = \sum_{i=1}^{n} CS(Q^*_i) . \tag{A.28}$$

That is, 1's SPF equals the sum of the consumers' surpluses for products in which 1 is an input.

Similarly, if w falls to w',

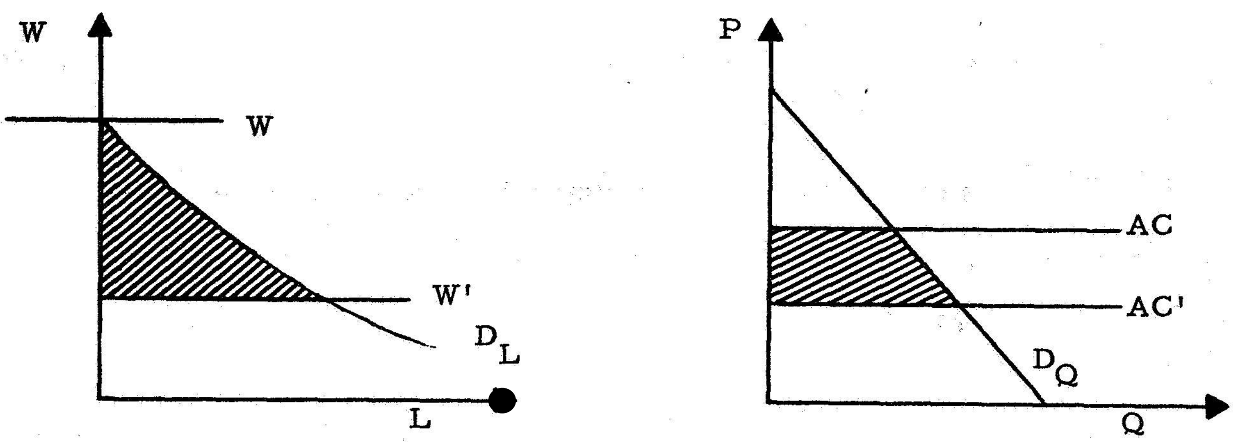
$$SPF(L') - SPF(L^*) = \sum_{i=1}^{n} \left[CS(Q'_i) - CS(Q^*_i) \right] . \tag{A.29}$$

That is, the change in the factor SPF is equal to the sum of the changes in output market surpluses.

Finally, because technological advance often introduces "new" intermediate products into the production of final goods, it is necessary to deal somehow with this issue. The above analysis provides a method. "Newness" is relative; few products are new in the sense of suddenly appearing. More often than not they have been in existence for some time, but have not been economical in production.

With this interpretation, advances in technology often make economical a previously non-economical intermediate product. If this is the case, then the change in consumers' surplus associated with the appearance in production of the "new" economical input is now the area under the factor demand curve, as shown in Figure A.3.

Figure A.3



Panel A   Panel B

At the old cost, w, factor 1 is not used in production. If a technological advance reduces the cost of 1 to w' and, thus, lowers the production cost of output from AC to AC', then the change in consumers' surplus (the shaded area in Panel B) is equal to the area under D_L above the new, lower cost, which is precisely the change in 1's SPF.

In conclusion, if one is willing to assume that industries are characterized by constant cost, and that factor market supplies are, as well, infinitely elastic, then changes in consumers' surplus generated by technological advance can be determined in factor markets. In particular, changes in SPF brought about by technological change will be equal to the corresponding changes in consumers' surplus due to lower product prices.

The above results provide the theoretical basis for measuring "cost savings" in intermediate markets and interpreting them as changes in consumers' surplus. For example, referring to Figure A.2, note that the change in SPF can be empirically approximated by

$$CR = (w - w') \times L' \tag{A.30}$$

The quantity CR, of course, can be interpreted as the "cost reduction" or "cost saving" in the intermediate market induced by the technological advance. Had technology not advanced, the per unit price of ℓ would have been w and the total cost of the amount L would have been higher than the amount $(w - w') \times L'$. Thus, the "cost savings" experienced in the factor market are approximately equal to the change in consumers' surplus generated by the advance.

Actually CR overstates the change in SPF, though in general the error is quite small. The precise magnitude of the error is given by

$$\left(\frac{t}{z}\right)\left(\frac{L'}{w'}\right)\left(w - w'\right)^2 \qquad (A.31)$$

where t is the elasticity of D_L at L'. For the purposes of this study, however, the exact error adjustment is not crucial; more importantly the results provide a basis for estimating the dispersed economic benefits of advancing technology by measuring "cost savings" in a single intermediate market.

In the case of a "new" intermediate good (see Figure A.3) a "cost savings" approximation to the change in SPF would produce rather large errors and it is, therefore, necessary to measure SPF directly. In this case, standard econometric methods can be used to estimate D_L and SPF can be derived through integration of the estimated demand curve.

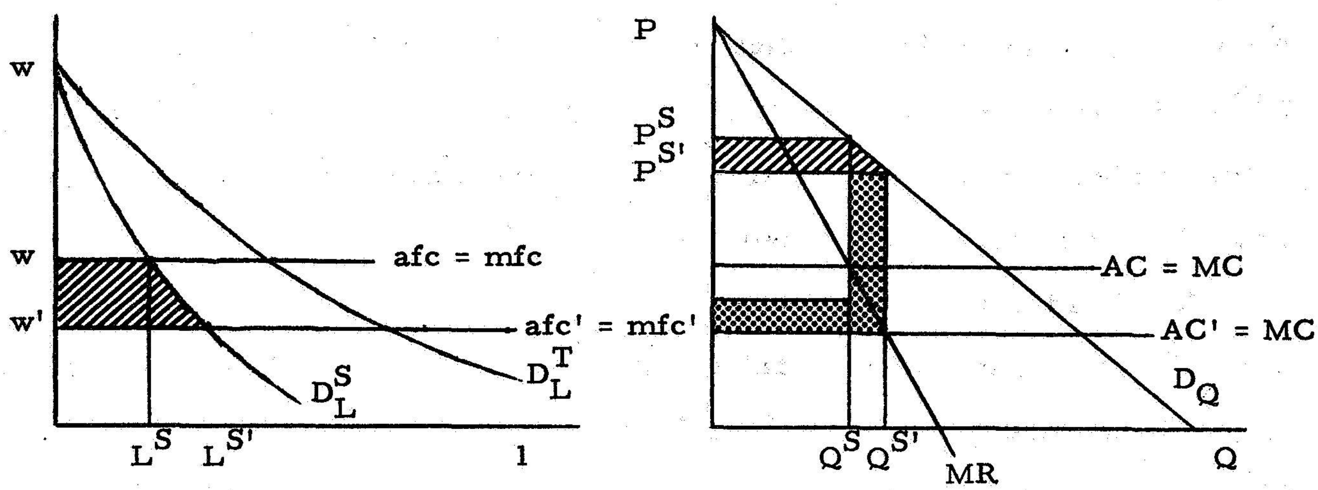
III. Price Searching in the Output and Factor Markets

Next are considered two different cases where "price taking" is replaced by "price searching". In the first, the consequences of monopoly in the sale of output are investigated, and in the second, the consequences of monopoly in the sale of input. Both require that attention be paid to the "other" source of benefits -- profits. Whereas in the "price taking" case no profits prevail, in either of these price searching cases, changes in technology produce economic profits to producers.

A. Monopoly in the Sale of Output

Consider monopoly in the output market. Assume that l is used in a single output Q and that all the assumptions--linear output demand, constant costs, etc.--hold, except instead of many output sellers, there is now only one. In this case, the output seller will equate marginal revenue (MR) with marginal cost (MC) and equilibrium output will be less than in the price taking case.

Figure A.4



Panel A   Panel B

Referring to Figure A.4, the monopolist's demand for labor, D_L^S, is now to the left of the demand in the price taking case (D_L^T). D_L^S is found by replacing Q in equation (A.11) with the monopolist's equilibrium output (i.e., Q where MR = MC). In particular, with the assumed conditions the monopolist's demand for l is given in equation (A.32).

$$D_L^S = A^{-1}\left(\frac{r\alpha}{\beta w}\right)^{1-\alpha} \frac{1}{2b}\left[a - A^{-1}\left(\frac{r}{\beta}\right)^{\beta}\left(\frac{w}{\alpha}\right)^{\alpha}\right] \quad (A.32)$$

Comparing (A. 32) with (A. 11) indicates D_L^S is precisely one-half the demand under conditions of price taking. Note, however, that it is still assumed that the monopolist is a "price taker" in the intermediate good market and that the intermediate good is produced under conditions of constant cost.

By equating marginal revenue with marginal cost, the monopolist maximizes profits. The equilibrium levels for output, output price and the quantity of factor 1 are indicated in Figure A. 4 by Q^S, P^S, and L^S. (The factor k is not shown.) The precise values of these variables, in terms of the given parameters, are easily determined, but for immediate purposes are not important.

Now if a technological change occurs which reduces the average factor cost (afc) and marginal factor cost (mfc) of 1 to w', the monopolist will increase output to $Q^{S'}$ and the quantity of 1 demanded to $L^{S'}$. In this case the increase in consumers' surplus (ΔCS) is indicated by the cross-hatched area in Panel B, Figure A. 4. As price falls from P^S to $P^{S'}$, this area represents the increase in consumers' surplus. However, this is not the only consequence of the technological change.

Indeed, the monopolist's profits have also increased. The shaded area in Panel B, Figure A. 4, represents the increase in profits ($\Delta\pi$) to the seller of Q. The economic benefits, as defined here, of the technological advance are thus the sum of the shaded areas in Panel B, Figure A. 4.

On the other hand, the shaded area in Panel A, Figure A.4, is the increase in SPF (ΔSPF). As indicated earlier, because measurement in the intermediate market is often "easier" than in the output market, it is important to know how ΔSPF is related to ΔCS and $\Delta\pi$. Under these special circumstances, a relatively easy calculation shows that

$$1.5\ \Delta SPF = \Delta CS + \Delta\pi \tag{A.33}$$

With the assumed linearity of demand, and letting ΔCS^T be the change in consumers' surplus that would have prevailed if the output market had been a price taking market, then the following relationships are easily verified:

(1) $\Delta SPF = \frac{1}{2}\Delta CS^T$ (3) $\Delta CS = \frac{1}{4}\Delta CS^T$

(2) $\Delta\pi = \frac{1}{2}\Delta CS^T$ (4) $\Delta WL = \frac{1}{4}\Delta CS^T$

where ΔWL is the increase in "welfare loss" associated with monopoly.

Though equation (A.33) is "special" and rests on the stated assumptions, it provides a basis for estimating the economic benefits of technological advance through measurement in the intermediate market. As before, define the technological advance's "cost savings" (CR) at the new level of the factor 1 as in (A.30). Then as these cost savings are approximately equal to ΔSPF, it is known from (A.33) that

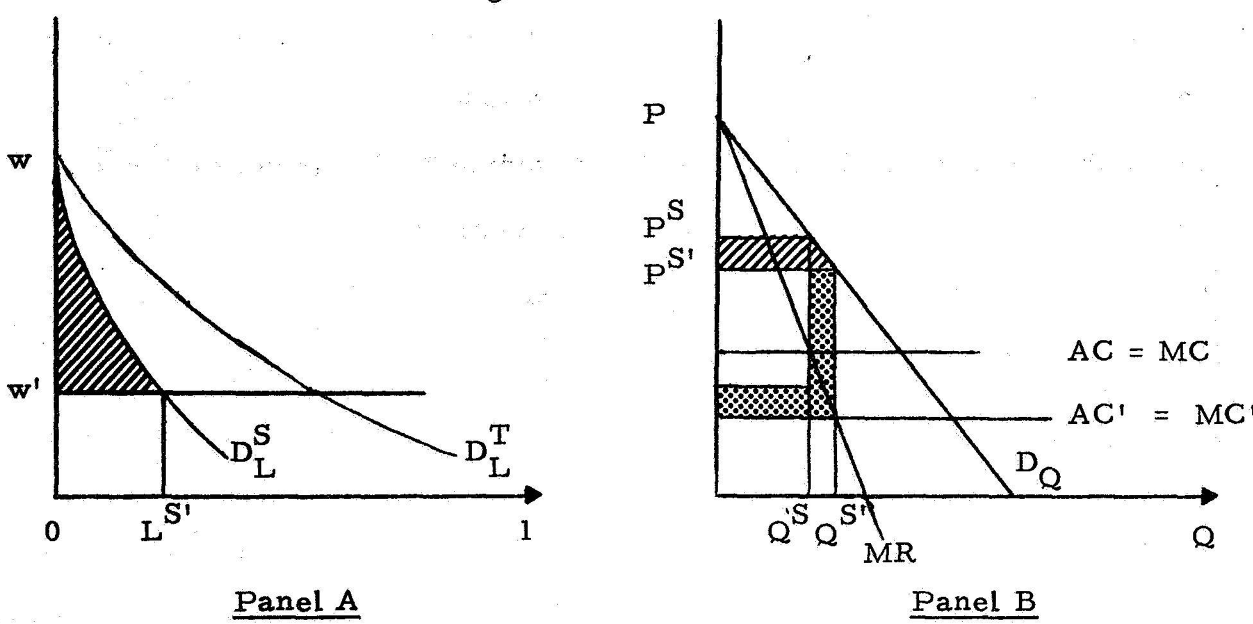
$$1.5\,CR \doteq \Delta CS + \Delta\pi \tag{A.34}$$

Equation (A. 34) rests on special, simplifying assumptions, and no doubt refinements will follow. Nevertheless, it provides a first approximation to an exceedingly complicated problem.

Note also, as in the case of price taking, since (essentially) consumer surplus and profits are additive, increasing the number of price searching sellers who employ l in production does not change the relationship in (A. 33).

In the case of a "new" intermediate product the relationship between Δ SPF and economic benefits is unaltered. However, the relevant area measuring Δ SPF is now the area under the monopolist's demand for l. Figure A. 5 illustrates this fact.

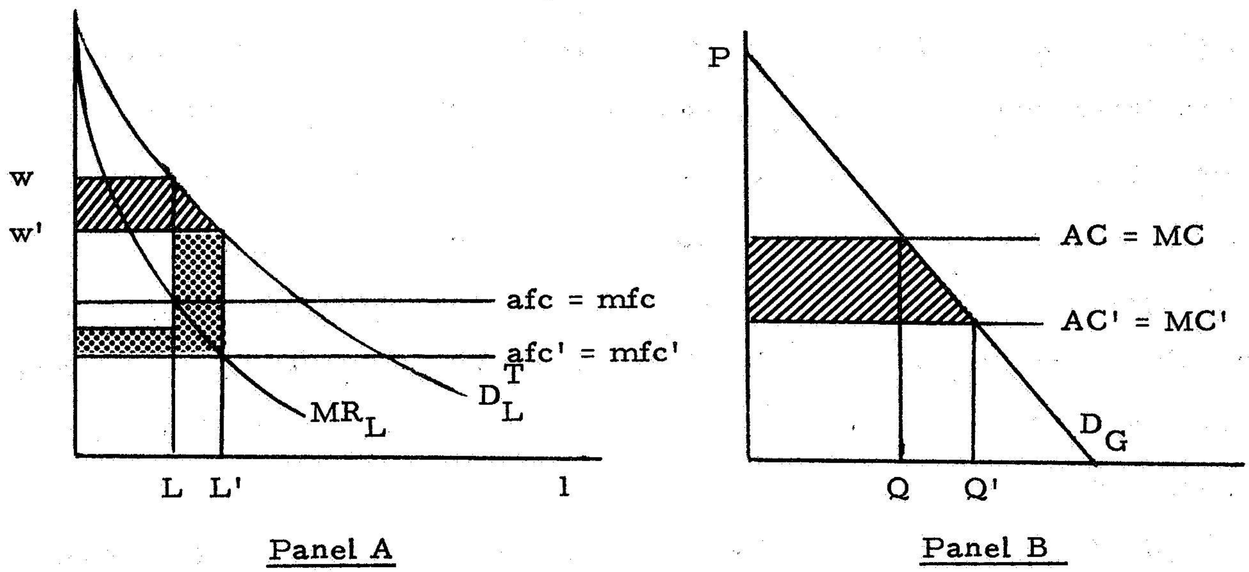
Figure A. 5



B. Monopoly in the Sale of Inputs

The case where the input, or intermediate good, seller is a monopolist is somewhat more complex. In this instance the assumptions are unaltered, except that it is assumed the factor seller adjusts his sales to equate marginal revenue and his (constant) marginal factor cost. The sellers of output are now assumed to be price takers, and again the output industry is characterized by constant cost.

Figure A.6



In Panel A, Figure A.6, if D_L^T is the market demand for the input l, then the monopolist seller of l will equate the marginal revenue (MR_L) with marginal cost. The pre-technical change equilibrium in the input market is indicated by the quantity L which is sold at a price per unit of w.

The producers of final output Q take the price of input, w, as given and proceed to the equilibrium indicated in Panel B. Because the monopoly price w is higher than the price that would prevail under price taking in the input market, output of the final good is smaller as well. In any case, if a technological change were to reduce the (constant) marginal factor cost of producing l, then its price would fall as the seller increased the quantity sold. Assuming the new equilibrium in the intermediate market is indicated by w' and L', then the cross hatched area in Panel A, Figure A. 6, is the increase in SPF associated with the technological change.

This cross hatched area is exactly equal to the change in consumers' surplus indicated in Panel B. This is so because from the point of view of producers of Q, the monopoly input prices are "indistinguishable" from other input prices they take as given. Thus, to this point this case is equivalent to the first discussed. However, the profits of the seller of l must be considered in order to arrive at the measure of economic benefits. The shaded area in Panel A, Figure A. 6, represents these profits. Thus, the sum of the two shaded areas in Panel A represents the economic benefits of the technological change.

Letting $\Delta\pi_l$ stand for the change in profits to the seller of l, then the economic benefits are approximated by $(w - w')(L') + \Delta\pi_l$, or $CR + \Delta\pi_l$. CR approximates ΔSPF which equals ΔCS in this case.

This may be a difficult quantity to estimate because firms often are reluctant to divulge information on product line profitability. Unfortunately, there is no easy way to eliminate this difficulty.

IV. Conclusion

The essential result of this appendix is that the area under a factor, or intermediate good, demand curve -- SPF -- is systematically related to the consumers' surplus associated with final goods using the factor in their production. In particular, in the case where outputs and factors are sold competitively and produced under conditions of constant cost, changes in SPF are equal to changes in consumers' surplus.

An important consequence of this result is that economic benefits -- changes in consumers' surplus -- can be monitored in intermediate markets. The practical benefits of this are two-fold. First, very often, data on intermediate goods are more easily accessable than data on final goods. More importantly, being able to access the consequences of a technological advance in a single market, rather than in a variety of output markets, makes the analysis tractable. Being able to analyze the obvious focal point of an advance reduces the complexities by an order of magnitude.

FOOTNOTES - APPENDIX A

1. See R. Schmalensee, "Consumer Surplus and Producer Goods," American Economic Review, September 1971; D. Wisecarver, "The Social Costs of Input Market Distortions," American Economic Review, June, 1974; R. Willig, "The Social Benefits of Technological Change," mimeo, 1975.

APPENDIX B:

TELEPHONE CALLS AND PERSONAL INTERVIEWS MADE AS PART OF CASE STUDY INVESTIGATIONS

APPENDIX B:

TELEPHONE CALLS AND PERSONAL INTERVIEWS MADE AS PART OF CASE STUDY INVESTIGATIONS

I. CRYOGENIC MULTILAYER INSULATION

Location	No. of Respondents
Air Products & Chemicals Inc.	3
Airco Cryoplants Corporation	2
American Railroad Association	1
American Trucking Association	3
Anemostat Products Division of Dynamics Corp. of America	1
Automobile Manufacturers Association	2
Belco Petroleum	1
Chemetron Corporation	2
Chicago Bridge & Iron	1
Cryogenic Associates	1
Cryogenic Society of America	1
Cryogenics & Industrial Gases	1
CVI Corporation	1
Denver Research Institute	3
Gardner Cryogenics	3
Girard Bank	1
Kansas Refined Helium	2

King-Seeley Thermos Company	2
Linde Division of Union Carbide Corporation	5
McGregor-Doninger	1
Michigan Wisconsin Inc.	1
NASA Lewis Research Center	2
NASA Marshall Space Flight Center	1
NASA Office of University Affairs (Washington, D.C.)	1
Perlite Manufacturing Company	1
Princeton University (Department of Mechanical Engineering)	2
Rockwell International	3
Standard Packaging Association (also known as National Metalizing)	1
Stanford Research Institute	1
Studley Shupert Company	1
Transportation Consultants	1
Union Carbide Corporation	7
U.S. Bureau of Mines	3
U.S. Bureau of Motor Carrier Safety	2
U.S. Department of Transportation - Hazardous Materials	3
U.S. National Bureau of Standards	1
University of Pennsylvania (Department of Chemistry)	1

II. GAS TURBINE TECHNOLOGY

Location	No. of Respondents
Cincinnati Gas and Electric	1
Columbus & Southern Ohio Electric	1
Delmarva Power and Light	3
Offshore Power Systems	1
Philadelphia Electric Company	2
University of Pennsylvania Library	1

III. INTEGRATED CIRCUITS

Location	No. of Respondents
General Instrument Corp, Semiconductor Component Div.	1
Hewlitt-Packard	1
National Semiconductor	2
NASA, Goddard Space Flight Center	4
RCA, Electric Components Division	2
RCA, Sarnoff Research Laboratory	2
Texas Instruments Corp.	1
Transistor Electronic Corp.	1
Western Electric, Bell Laboratories	1

IV. NASTRAN (includes survey respondents)

Location	No. of Respondents
AVCO Aerostructures Division	1
Aerojet Nuclear	1
Battelle Mem. Inst.	1

Bell Helicopter	1
Bendix Corp	1
Binary Systems Inc.	1
Brown and Root	1
Bucyrus-Erie Co.	1
Cessna Aircraft	1
Charles Starkdrager Labs	1
Chrysler Corp.	1
Combustion Engineering	1
Computer Sciences Corp.	3
Control Data Corp.	1
Esso Production Research Co.	1
Ford Motor Co.	2
General Dynamics	1
General Electric	1
Grumman Aircraft - Structural Div. and Data Processing Div.	1
Harris Electronics	1
Hek Corp.	1
Hercules Inc.	1
Honeywell Information Systems	1
IBM	1
Lockheed Electronics Corp.	1
MacNeal-Schwendler Corp.	1
McDonnell Douglas	2
Newport News Shipbuilding and Dry Dock Co.	1

Northrop Corp	1
Picatinny Arsenal	1
Pratt & Whitney Aircraft	2
Pullman-Standard	1
RCA	1
Raytheon	1
Rockwell International	1
Rohr Industries	1
Sandia Lab	1
Simpson Gumpertz & Heger	1
Southwest Research Inst.	1
Sperry-Univac	4
Structural Design Research Corp.	1
Swanson Analysis Systems	2
TRW	3
Teledyne	1
U.S. Navy, Naval Undersea Center, San Diego	1
Vought Systems Div.	1
Westinghouse Electric Corp.	1
Xerox Corp.	1

APPENDIX C:

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BIBLIOGRAPHY

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